THE DEPARTMENT OF DEFENSE

CRITICAL TECHNOLOGIES PLAN

FOR THE
COMMITTEES ON ARMED SERVICES
UNITED STATES CONGRESS

1 MAY 1991

Distribution/Availability of Report:

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THE DEFENSE CRITICAL TECHNOLOGIES PLAN OF 1991

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I. SUMMARY

The purpose of the Department of Defense Critical Technologies Plan (DCTP) is to describe 21 technologies considered essential for maintaining the qualitative superiority of U.S. weapon systems and to outline an investment strategy to manage and promote the development of these technologies. The Defense Critical Technologies are the leading edge of the DoD Science and Technology (S&T) program. While all S&T efforts are fundamental to achieving continued improvement in military capabilities, the Defense Critical Technologies represent those technologies that are likely to set the pace of innovation in the development of advanced weapon capabilities and the evolutionary modernization of today's systems.

This third annual plan is more comprehensive than earlier editions. A new section has been added to document funding levels for individual Defense Critical Technologies for the relevant S&T Program Elements (PEs) (Annex A); moreover, the individual detailed technology plans (Annex B) provide greater detail on specific milestones and technology objectives, as well as a more comprehensive discussion of related private sector and non-DoD government programs. The plans also include assessments of international technology developments and trends.

The 1991 plan reflects a substantially increased level of participation from the Services, industry and interested Federal agencies, particularly in the generation of the detailed technology plans. The contributions of the Aerospace Industries Association, the Electronic Industries Association, and the National Security Industrial Association were particularly valuable. The Department of Energy, the National Aeronautics and Space Administration, the National Institute of Standards and Technology (Department of Commerce), and the National Science Foundation provided extensive information regarding relevant non-DoD programs and helpful comments on specific technology plans. In addition, the 1990 Defense Science Board (DSB) summer study provided a solid basis and framework for this DCTP. A wide range of DoD organizations were also integral to the preparation of this plan, particularly the Joint Staff and the DSB. The contributions of all are acknowledged.

The Secretary of Defense stated his top priorities on several occasions. These priorities not only recognize the complexities of national security and future uncertainties in the world, but also provide objectives for research and development in DoD. These priorities are:

- Quality Personnel
- Technological Superiority
- Efficient Acquisition
- Robust Nuclear Posture and Strategic Defense
- Versatile, Ready, Deployable, Sustainable Force
- Continued Maritime Superiority
- Reserve Forces and Mobilization
- Special Operations Forces

The DDR&E has established three streams that seek to:

1.) Provide for the orderly, evolutionary improvements in weapon systems, their subsystems, and support systems, such as the training, logistics, and defense industrial base infrastructure. These improvements must be responsive to future security threats and environments. The Services are the primary agents for these evolutionary technology changes.

2.) Generate innovative, highly leveraged breakthrough technology and insert this technology efficiently into our military capability. Here the Defense Advanced Research Projects Agency (DARPA) plays a major role, as does the Strategic Defense Initiative (SDI) program, the Balanced Technology Initiative, and the research organizations of the military departments.

3.) Seek technology trump cards (to be played every 5 to 10 years) to sustain long-term dominance in the technological arms race. Recent examples of such trump cards are stealth aircraft; older examples include the atomic bomb and the Polaris System. Trump cards bring about major shifts in how we think about and conduct war.

The S&T program is the principal vehicle for implementing these three streams. The Critical Technologies program focuses primarily on stream two, and contributes to streams one and three. The Critical Technologies program consists of 21 Defense Critical Technologies. They are listed in Table 1.

This year's planning process confirms the priority placed on these technologies by DoD in the 1990 Critical Technologies Plan. These technologies were originally selected on the basis of their contributions to maintaining the superiority of U.S. military weapon systems, primarily through their leverage on key subsystems. (The Defense Critical Technologies are discussed further in Chapter II. Brief technology plan summaries are presented in Chapter III, and the full technology plans are presented in Annex B.)

Tables 2A and 2B below show planned spending levels for the Defense Critical Technologies in FY 1991 as well as annual budget totals for FY 1992-97. These figures incorporate relevant funding from the DoD S&T program, including the Strategic Defense Initiative Organization (SDIO), which is a strong contributor to many of the Defense Critical Technologies. (Defense Critical Technologies funding is summarized further in Chapter IV and detailed at Annex A.)

The overall funding levels and objectives for development of the Defense Critical Technologies reflect the FY 1992 President's Budget. Recent management attention, including the 1990 Defense Management Review (DMR) initiated actions, has resulted in a strong emphasis on support for the Defense Critical Technologies, an emphasis that is reflected in these funding levels. Despite the fact that budget constraints will cause overall DoD RDT&E spending to decline over the coming years, funding levels for the Defense Critical Technologies have significantly increased in FY 1992 from the FY 1991 budgeted request and will remain stable or increase slightly. DoD's commitment to the Defense Critical Technologies will remain strong. The Defense Critical Technologies already represent a substantial focus within the combined S&T/SDIO technology development budgets, accounting for approximately 35 percent of projected FY 1992 spending. This share is projected to increase to approximately 40 percent of the total S&T/SDIO technology development budget by FY 1997. Without SDIO, the percent of critical technologies for FY92 is approximately 52%, a significant increase over the FY91 requirement.

DoD recognizes the need to ensure that its S&T resources — and particularly its Defense Critical Technologies budgets — are focused on high-payoff technologies that meet the most pressing current and emerging military needs. DoD is conducting an ongoing appraisal of the Defense Critical Technologies programs to ensure that the Services and Defense Agencies maintain proper emphasis on developing these technologies and to ensure that the goals of these programs remain consistent with DoD's overall S&T needs.

Table 1 Defense Critical Technologies

1	Semiconductor Materials & Microelectronic Circuits	The production and development of ultra-small integrated electronic devices for high-speed computers, sensitive receivers, automatic control, etc.
2	Software Engineering	The generation, maintenance, and enhancement of affordable and reliable software in a timely fashion.
3	High Performance Computing	High performance computing systems having 10^3 fold improvements in computation capability and 10^2 fold improvements in communication capability by 1996.
4	Machine Intelligence & Robotics	Incorporation of aspects of human "intelligence" into computational devices which enable intelligent function of mechanical devices.
5	Simulation & Modeling	Visualization of complex processes and the testing of concepts and designs without building physical replicas.
6	Photonics	Includes ultra-low-loss fibers and optical components such as switches, couplers, and multiplexers for communications, navigation, etc.
7	Sensitive Radar	Radar sensors capable of detecting low-observable targets, or capable of non-cooperative target classification, recognition, and/or identification.
8	Passive Sensors	Sensors not needing to emit signals to detect targets, monitor the environment, or determine the status or condition of equipment.
9	Signal & Image Processing	Combination of computer architecture, algorithms, and microelectronic signal processing devices for near real-time automation of detection, classification, and tracking of targets.
10	Signature Control	The ability to control the target signature (radar, acoustic, optical, or other) and thereby enhance the survivability of vehicles and weapon systems.
11	Weapon System Environment	A detailed understanding of the natural environment (both data and models) and its influence on weapons system design and performance.
12	Data Fusion	The machine integration and/or interpretation of data and its presentation in convenient form to the human operator.
13	Computational Fluid Dynamics	The modeling of complex fluid flow to make dependable predictions by computing, thus saving time and money previously required for expensive facilities and experiments.
14	Air Breathing Propulsion	Light-weight, fuel efficient engines using atmospheric oxygen to support combustion.
15	Pulsed Power	The generation of repetitive, short-duration, high-peak power pulses with relatively light-weight, low-volume devices for weapons and sensors.
16	Hypervelocity Projectiles & Propulsion	The ability to propel projectiles to greater-than conventional velocities (over 2.0 km/sec), as well as understanding the behavior of projectiles and targets at such velocities.
17	High Energy Density Materials	Compositions of high-energy ingredients used as explosives, propellants, or pyrotechnics.
18	Composite Materials	Two or more constituent materials that are combined together in such a manner to produce a substance possessing selected properties superior to those of its individual components.
19	Superconductivity	Makes use of the zero resistance property and other unique and remarkable properties of superconductors for creation of high-performance sensors, electronic devices and subsystems, and supermagnet based systems.
20	Biotechnology	The systematic application of biology for an end use in military engineering or medicine.
21	Flexible Manufacturing	The integration of production process elements aimed at efficient, low cost operation for small, as well as high, volume part number variations, with rapidly changing requirements for end product attributes.

Table 2.A. Funding for Critical Technologies (With SDIO) (Millions Then Year Dollars)

Technology	FY 1987-91 ACTUAL	FY 1991 REQ	FY 1991 ACT	FY 1992 REQ	FY 1993 REQ	FY 1994 REQ	FY 1995 REQ	FY 1996 REQ	FY 1997 REQ
1 Semiconductor Materials & Microelectronic Circuits	1,055	370	534	479	481	487	488	490	510
2 Software Engineering	384	115	133	149	148	153	155	156	157
3 High Performance Computing	414	80	108	172	219	273	301	349	350
4 Machine Intelligence & Robotics	551	116	162	148	142	145	144	144	143
5 Simulation & Modeling	1,230	202	300	334	343	340	335	344	344
6 Photonics	710	75	167	186	190	180	179	190	173
7 Sensitive Radars	669	110	180	196	201	192	188	191	192
8 Passive Sensors	2,065	460	428	530	554	523	512	514	509
9 Signal & Image Processing	753	130	221	235	230	232	234	240	219
10 Signature Control	* 572	*120	*120	*109	*102	*89	*87	*88	*88
11 Weapon System Environment	929	180	213	232	238	248	249	252	260
12 Data Fusion	288	50	98	106	109	108	98	98	83
13 Computational Fluid Dynamics	428	55	118	94	95	99	101	105	108
14 Air Breathing Propulsion	968	180	227	224	211	185	190	193	201
15 Pulsed Power	541	95	95	76	76	81	80	80	82
16 Hypervelocity Projectiles & Propulsion	710	120	153	183	205	201	200	197	198
17 High Energy Density Materials	409	76	82	84	86	95	93	98	98
18 Composite Materials	1,089	170	204	193	197	211	216	224	229
19 Superconductivity	345	88	58	56	61	64	54	65	57
20 Biotechnology	79	100	69	65	66	68	69	71	72
21 Flexible Manufacturing	105	17	27	25	28	29	31	32	31
Planned Total Funding for Defense Critical Technologies - S&T with SDIO	15194**	2909**	3684**	3874**	3972**	3991**	4006**	4107**	4112**
Projected Total Funding for all Technology Development Activities - S&T with SDIO	NA	9784	9048	11095	11413	11749	11501	10895	10542

Table 2.B. Funding for Critical Technologies (Without SDIO) (Millions Then Year Dollars)

Technology	FY 1987-91 ACTUAL	FY 1991 REQ	FY 1991 ACT	FY 1992 REQ	FY 1993 REQ	FY 1994 REQ	FY 1995 REQ	FY 1996 REQ	FY 1997 REQ
Planned Total Funding for Defense Critical Technologies - S&T without SDIO	10944**	1989**	3081**	3144**	3179**	3200**	3211**	3308**	3309**
Projected Total Funding for all Technology Development Activities - S&T without SDIO	NA	5324	6186	6015	6223	6339	6489	6770	6886

* Funding for this Critical Technology are unclassified totals only.

**Totals do not include funding for classified Signature Control efforts.

ACT - Actual Budget

REQ - Budget Request

Based on this ongoing appraisal, DoD may introduce fact-of-life changes into the FY 1993 budget and will provide guidance for the development of the FY1994–1999 FYDP. While recognizing the need for continuity, DoD will modify the milestones and the budgetary priorities for individual Defense Critical Technologies to reflect promising new technology developments and emerging military needs.

This plan consists of five chapters and two appendices. Chapter II discusses how the emerging security environment affects DoD's future military needs, describes how DoD's defense technology strategy is responsive to these future needs, provides an overview of the 21 Defense Critical Technologies, and describes key attributes of these technologies. Chapter III contains brief summaries of each of the 21 Defense Critical Technologies, and Chapter IV describes DoD's funding support for these technologies. Chapter V describes the overall DoD Science and Technology management process. Annex A provides detailed S&T funding summaries by fiscal year for each of the 21 Defense Critical Technologies. Annex B includes a description of the selection methodology and detailed technology plans for the 21 Defense Critical Technologies, including technology milestones and objectives, government and private sector R&D activities, industrial base profiles, and international assessments.

II. TECHNOLOGY INVESTMENT PLANNING

Emerging Security Environment Challenges to DoD

In a major address on national security at the Aspen Institute in August 1990, President Bush underscored the importance of defense R&D: "To cope with the full range of challenges we may confront, we must focus on readiness and rapid response. And to prepare to meet the challenges we may face in the future, we must focus on research — an active and inventive program of defense R&D."

Based on this mandate and in concert with global political events and military trends, DoD developed the Critical Technologies Plan provided here.

The following threats still challenge us:

a) The dissolution of the Warsaw Pact as a military organization is changing the U.S. national security problem; but the Soviet Union continues to be a potential threat to the U.S. While our national defense strategy no longer focuses primarily on Europe and the possibility of Soviet aggression there, we must not discount that nation as a formidable military force.

b) Second, we must deal with the rapid diffusion of advanced weapon technologies to regional powers, including potentially unpredictable and ruthless regimes.

c) Growing, too, is the potential for smaller conflicts, ranging from violence spawned by narcotics trafficking, to terrorism, and to insurgencies.

In tandem with this emerging security environment, the United States is likely to face new resource constraints. DoD plans a 25 percent reduction in active forces in the next five years, and procurement outlays are programmed to fall from $79.1 billion in FY 1991 to $71 billion in FY 1996.

All of these factors point to the importance of a strong and stable research and development posture that is tied directly to our defense strategy, funded appropriately, and managed effectively.

DoD Science and Technology Strategy — Responding to the Challenges

Our strategic vision for defense technology takes a twenty-year view as it looks at three streams of technology:

1) Putting in place a process that provides orderly, evolutionary improvements in weapon systems, their subsystems, and support systems, such as the training, logistics, and defense industrial base infrastructure. These improvements must be responsive to future security threats and environments. The Services are the primary agents for these evolutionary technology changes.

2) Generating innovative, highly leveraged breakthrough technology and inserting this technology efficiently into our military capability. Here the Defense Advanced Research Projects Agency (DARPA) plays a major role, as does the Strategic Defense Initiative (SDI) program, the Balanced Technology Initiative, and the Services.

3) Seeking technology trump cards (to be played every 5 to 10 years) to sustain long-term dominance in the technological arms race. Recent examples of such trump cards

are stealth aircraft; older examples include the atomic bomb and the Polaris system. Trump cards bring about major shifts in how we think about and conduct war. Steady generation of such trump cards will assure long term dominance in defense technology for this country.

We need all three — evolutionary improvements, breakthrough technologies, and trump cards; and we need to manage defense S&T to allow for the development and application of all three. To do so, our strategy focuses on several themes:

1) Modularity in design and construction of platforms. We do not expect many new starts of major weapon platforms in the next ten to twenty years. Therefore, we plan on enhancing the capability and longevity of those systems by designing them with modular improvements in mind.

2) A systematic program to upgrade key subsystems of existing weapon systems (e.g., avionics, propulsion plants, weapons, communications, and countermeasures) as threats evolve. The wealth of technological opportunities will be exploited for potential applications to provide superior weapon performance and affordability.

3) A stronger focus on our S&T (6.1, 6.2, and 6.3a) programs to provide the technology push for future capabilities, and supported by a restructured and modernized in-house Research, Development, Test, and Evaluation (RDT&E) establishment.

4) Producing quality products at an affordable cost by keeping the mainstream of system and subsystem developments evolutionary, while preserving opportunities for revolutionary, high-leverage, timely improvements.

5) A stronger combination of innovation in technology and in operational concepts by identifying and demonstrating the opportunities for highly leveraged technology insertions and their interaction with operational innovations.

6) Radical acceleration of the development, introduction, and use of flexible manufacturing technology and training technology.

7) Stronger emphasis on an integrated approach to engineering analysis, modeling and simulation, gaming, prototyping, development, test and evaluation, and net technical assessment.

8) Forecasted mission needs should influence, in large measure, particular program or technology development efforts.

One of the primary tools by which we will manage the implementation of this technology strategy is the Defense Critical Technologies Plan. Each technology identified this year was selected based on its individual merits. We analyzed how each technology would contribute to improving military capabilities for a wide range of scenarios of military conflict, and we selected technologies and the technical objectives for them on the basis of maximum payoff. The process is described more fully in Annex B. Collectively, these technologies reflect, one aspect of DoD's long-term, consistent approach to S&T.

In 1990, DoD modified several of the technologies (which are reflected in minor title changes). These changes more accurately describe recent technological developments and DoD's current areas of emphasis within these broad technology areas. DoD also added a new technology, flexible manufacturing (not to be confused with the long-standing Manufacturing Technology (ManTech) Program), to acknowledge the increased importance of maintaining technological superiority in advanced manufacturing process technologies.

The Defense Critical Technologies Plan gives us a means to identify and describe these technologies and to develop and apply them to those military systems and subsystems that will give us the highest leverage.

To do this we have taken the list of 21 technologies and placed them in five clusters (see Figure 1). The clusters are a manageable way of looking at the vast array of opportunities available to us. They are a plausible way of organizing for action, a convenient way to illustrate broad themes. Our clusters also demonstrate the high degree of interdependence among these technologies in spite of their diversity. The clusters and their associated technologies are not unique, but they are useful in providing broad objectives.

Figure 1 Defense Critical Technologies Clusters

Critical Technologies	Computing/ Information	Sensing	Materials & Manufacturing	Energy & Material Flow Management	Infra-structure
1 Semiconductor Materials & Microelectronic Circuits	●	●	●		
2 Software Engineering	●		●	●	●
3 High Performance Computing	●	●	●	●	●
4 Machine Intelligence & Robotics	●		●	●	●
5 Simulation & Modeling	●			●	●
6 Photonics	●	●			
7 Sensitive Radars	●	●			
8 Passive Sensors		●	●		
9 Signal & Image Processing	●	●			
10 Signature Control		●	●		
11 Weapon System Environment		●			●
12 Data Fusion	●				
13 Computational Fluid Dynamics	●		●	●	
14 Air Breathing Propulsion			●	●	
15 Pulsed Power			●	●	
16 Hypervelocity Projectiles & Propulsion	●		●	●	
17 High Energy Density Materials			●	●	
18 Composite Materials			●	●	
19 Superconductivity		●	●	●	
20 Biotechnology			●		
21 Flexible Manufacturing			●		●

- The first two clusters are computing/information and sensing. These embrace technologies that primarily involve the processing, acquisition, manipulation, synthesis, transmission, simulation and denial of information. They form the core of advanced C^3I, electronic warfare, target acquisition, and guidance. The strong information emphasis in the Defense Critical Technologies corresponds to the growing importance of information in both deterrence and modern combat. The ability of the United States to acquire and effectively use information, while denying accurate information to adversaries, can help compensate for planned reductions in U.S. force structure and forward deployed assets. Moreover, the development of "brilliant" stand-off weapons and other systems with advanced automatic target recognition capabilities — innovations that are highly dependent upon continued progress in the information and sensing areas — also will become important force multipliers that greatly enhance U.S. capabilities to project military power in the coming decades.

- Materials and manufacturing processes are critical to DoD's ability to translate advanced technologies into high quality, reliable, and affordable equipment. Regardless of their potential in the laboratory, advanced defense technologies cannot enhance military capabilities unless they are rapidly and efficiently incorporated into fielded systems. Innovative process technologies are a key to helping reverse long-term acquisition trends toward escalating unit costs, lengthening lead times, and increasing difficulties in the incorporation of technological advances into operational systems. These trends, if not addressed, have serious implications for the ability of DoD to sustain its planned force structure in an era of constrained procurement budgets, as well as DoD's ability to rapidly field new systems to counter unanticipated technological vulnerabilities.

  The addition of flexible manufacturing to the 1991 list of Defense Critical Technologies -- the only such change this year -- reflects DoD's growing appreciation of the importance of process technology in the acquisition and support of advanced weapon systems. Sophisticated flexible design and production techniques can help in reducing costs, compressing development cycles, and improving the quality and reliability of advanced military equipment.

  The other technologies in the materials and manufacturing processes cluster also have a strong process orientation and, as a group, can have an important impact on improving system acquisition. For example, in software -- which accounts for approximately 10 percent of DoD's procurement and O&M budget — innovations in the generation of reliable and maintainable software code for sophisticated applications would yield dramatic procurement savings, eliminate a major source of program delays, and greatly enhance the reliability of U.S. weapon systems.

- In comparison with the other clusters, the energy and material flow management area includes more system-specific technologies that are vital to upgrading the performance of existing weapon systems, as well as less mature technological areas that have the strong potential to provide "breakthrough" capabilities that are important to sustaining U.S. technological preeminence into the next century. For example, the development of advanced aircraft turbine engines, air-breathing propulsion, more lethal munitions, and high energy density materials are integral components in DoD's growing emphasis on enhancing military capabilities through subsystem upgrades that incorporate advanced technology. On the other hand, pulsed power, hypervelocity projectiles, and superconductivity could lead to radically new weapons or order-of-magnitude improvements in the capabilities of existing systems.

- Fifth is the broad area of technical infrastructure related to the vast efforts of DoD to employ the best technology and equipment for training, logistics, and control. It includes such technologies as simulation and modeling, information systems, and training systems.

In summary, the Defense Critical Technologies broadly support DoD's future needs for enhanced capabilities for acquiring, manipulating, and effectively using information; for the development of more efficient process and product technologies to improve system acquisition; and for technologies that contribute to both continual, evolutionary improvements in the capabilities of major weapon systems, as well as lay the groundwork for breakthrough innovations to ensure U.S. technological superiority in the coming decades.

Defense Technology Program Objectives

The general objectives are unchanged from last year and are summarized as follows:

Primary:

- To provide the major advances that will permit the timely design, manufacture, and fielding of advanced weapon systems and subsystems, as well as supporting systems for all parts of the military forces.

Secondary:

- To select and train future leaders and experts in defense-critical advanced technology areas; to make them available for downstream R&D programs;
- To transfer the appropriate technologies to private industry in order to increase international competitiveness.

Supporting objectives:

- Effective management of resources (skills, facilities, budgets);
- Protection of scientific and technological achievements from transfer to unauthorized parties;
- Appropriate, effective, and timely communications within the Department, and with the Congress, the scientific community, and industry;

For each of the critical technologies, specific technical objectives for the next ten to twenty years have been established, with inputs from the Services and the Defense Agencies and the help of the Defense Science Board and the Service laboratories. Defense industry associations also provided their inputs. These are described in Chapter 3 and Annex A.

Critical Technologies Attributes

Taken as a whole, the Defense Critical Technologies have several key attributes that are significant for DoD S&T management, including:

- Criticality;
- Continuity;
- Interdependence; and
- Dual-use.

Criticality. The technical achievements planned for the Critical Technologies are essential for the fielding of superior quality forces in the future.

Continuity. Except for the addition of flexible manufacturing, this year's list of Defense Critical Technologies is identical to that published in 1990 and has changed little since the list was first released in 1989. Meanwhile, some technical objectives have been changed as the result of reported accomplishments and evolving military needs.

Interdependence. In general, progress in any single Defense Critical Technology depends in part on parallel advances in a variety of other important technologies. For example, advanced microelectronic circuits are central to the development of sophisticated computer architectures. In turn, improvements in computing capabilities are a prerequisite to desired innovations in simulation and modeling, computational fluid dynamics, signal processing, data fusion, machine intelligence, flexible manufacturing, and other important fields, including (to complete the circle) semiconductor electronics. This high degree of technological interdependence requires a balanced approach to technology development. Devoting an excessive amount of R&D resources to any single technology or small group of specific technologies is unlikely to achieve the desired results if such unbalanced efforts retard the development of supporting technologies.

While the Defense Critical Technologies are highly interdependent, as a group they are also extremely diverse. Microelectronic circuits, signature control, biotechnology materials, and high energy density materials incorporate a broad range of scientific disciplines and correspond to a wide set of future military needs. Moreover, advances in any specific Defense Critical Technology require a broad-based, interdisciplinary R&D approach. For example, unlocking the revolutionary potential of superconductivity requires the integration of expertise from fields such as materials science, physics, computer science, and chemistry. The breadth of the technologies and the diverse expertise required to achieve advances in any specific technology illustrate the importance of a broad S&T base as a critical foundation in the development of advanced weapon systems.

Dual-use. Finally, the Defense Critical Technologies shows that modern military power is largely dependent upon dual-use technologies. At least 15 of the 21 Defense Critical Technologies, in addition to contributing to vital DoD missions, have significant commercial applications or potential. For example, advances in semiconductor materials and microelectronic circuits, software engineering, and biotechnology will yield substantial benefits to both DoD and the civilian economy. In contrast, only six of the DoD Critical Technologies, sensitive radars, signature control, weapon system environment, pulsed power, hypervelocity projectiles and propulsion, and high energy density materials are largely militarily unique.

The importance of dual-use technologies is further illustrated by the extensive overlap among the Defense Critical Technologies and comparable collections of commercially oriented technologies. Except for the six military-specific technologies, all of the Defense Critical Technologies correspond closely to one or more of the technologies highlighted in the Department of Commerce's 1989 list of emerging technologies as well as the March 1991 list of National Critical Technologies compiled by an advisory panel sponsored by the Office of Science and Technology Policy. Moreover, this convergence of military and commercial technology is likely to become more pronounced as advanced weapon systems become increasingly dependent upon information technologies, which are also vital to a broad range of commercial and industrial applications.

III. SUMMARY OF DEFENSE CRITICAL TECHNOLOGIES PLANS

This chapter provides brief summaries of the detailed technology plans for each of the 21 Defense Critical Technologies. These summaries include a concise description of the technology area, its application to future military systems, illustrative technology objectives and milestones, and the potential impact of the technology on the defense industrial base. Detailed information on these and related issues for each of the Defense Critical Technologies may be found in the comprehensive technology plans provided in Annex B.

1. ***Semiconductor Materials and Microelectronic Circuits*** encompasses the production and development of ultra-small integrated electronic devices for high-speed computers, sensitive receivers, automatic control, etc. The principal component fields of this critical technology are:

- Very large scale integrated circuits
- CAD for complex circuits
- High resolution lithography
- Analog/digital converters
- Power converters
- Micro- and millimeter wave sources and amplifiers
- Transmit/receive modules and arrays
- Signal control components
- Radiation hard isolation technology

The information processing capability provided by advanced microelectronic devices is truly pervasive in U.S. weapon systems, and is likely to become even more so. The availability of microcircuit technology continues to have two major effects on the development of new systems. First, the technology makes it possible to extend the flight control envelope of aerodynamically unstable aircraft, and second the technology allows the creation of radically new systems, like smart weapons. The systems made possible by this technology provide a qualitative advantage to U.S. forces by increasing the soldier's ability to acquire and act upon information and to deliver weapons against the adversary. "Ultra-small" circuits have allowed a shrinking of the volume of computational capability required by smart weapons. As these devices have become smaller, the manufacturing technology required to fabricate them becomes more highly specialized and requires continued research and development into processes, equipment, and materials. Much of the R&D thrust towards higher levels of miniaturization and increased performance is applicable to both the defense and commercial sectors; however, battlefield requirements for ruggedness, radiation-hardness, and extreme environments are unique to defense systems. Research in microelectronic circuits is aimed at achieving several major objectives for weapon systems. Central to DoD requirements is a need to perform signal processing at gigahertz speed levels and beyond. This will require components of advanced materials whose feature sizes are below one-quarter micron. In addition, DoD is developing ever-increasing levels of integration with the objective of wafer-scale integration of logic and memory to further reduce system size and cost. Detailed plans for the development of this critical technology are in Annex B, on page 1-1.

2. ***Software Engineering*** refers to the generation, maintenance, and enhancement of affordable and reliable software in a timely fashion. The principal component fields of this critical technology are:

- Software and system engineering processes and environments
- Real-time/fault-tolerant software
- Reuse and re-engineering
- Software for parallel and distributed heterogeneous systems
- High assurance software

The "smarts" of major defense systems, including weapon systems, information systems, and scientific/engineering systems, are usually embodied in software. Indeed, software capability has become a principal determiner of overall weapon systems capability. In theory, software has enormous potential power and flexibility. In practice, software development and management is a complex, labor-intensive process, and our software capability is bounded by the extent to which the complexities in this process can be managed through attention to process and use of tools. Automated tools, linked together in software and system engineering environments that coordinate and manage tool operation, can take over many of the details of software engineering activity, yielding more cost-effective processes and potentially larger and more powerful systems. By 1993, DoD will be making experimental use of software engineering environment frameworks supporting use of commercially compatible tools to manage large scale software development. Design of embedded defense software usually involves management of "real-time" constraints and deadlines for processing of incoming sensor data and generation of outgoing control signals. In the presence of unreliable system components, the software must be designed in a fault-tolerant manner. By 1995, DoD will be demonstrating distributed operating systems supporting time-constraints and fault-tolerance. Much of the DoD software expenditure is in post-deployment activity or software logistics. Technology to facilitate management and re-engineering of existing assets can not only reduce post-deployment costs, but also greatly facilitate creation of reusable software assets such as simulation. The principal opportunity in reuse is megaprogramming, which is the development and management of DoD software applications on a component-by-component basis rather than instruction-by- instruction. Megaprogramming technology includes software component definition and composability technology, software tools and environments supporting component composition, software component libraries, associated capabilities for software electronic commerce, and software process models supporting reuse. By 1998, DoD will demonstrate the ability to develop domain-specific systems architectures and reusable components compliant with these specifications. High performance computing systems of all kinds, including scientific/engineering systems, embedded systems, and the leading edge information systems, employ parallel and distributed processing. By 1994, DoD will demonstrate systems software for survivable distributed and parallel computing. High assurance software technology is required in the design of safety-critical systems, including most weapon systems, and secure systems, in which confidentiality and integrity must be assured to a high level of confidence. By the mid-1990s, DoD will demonstrate highly secure and reliable operating systems, database management systems, and other related components. In each of these software technology areas, DoD must work to stimulate commercial development of off-the-shelf products that can be made to meet military needs. Detailed plans for the development of this critical technology are in Annex B, on page 2-1.

3. ***High Performance Computing*** – Rapid improvements in the performance and cost effectiveness of computer hardware, enabled by integrated microelectronics technologies, have spread computing into all areas of military and civilian life. Performance is expected to exceed one trillion operations per second (teraops) by the mid 1990s as a result of the Presidential Initiative in High Performance Computing and Communications described in a supplement of the President's FY 1992 budget submission. Teraops computing systems will require billion bit per second (gigabit) networks. DoD is fully supporting this initiative in the DARPA HPC program. The major technology areas are:

- High performance computer systems
- Advanced software technology and algorithms
- High performance networking
- Basic research and human resources
- Defense specific technologies

These major technology areas can be characterized as follows: High performance computer systems developments are in four main areas: research for future generations of computing systems, system design tools, advanced prototype systems, and evaluation of early systems. Systems capable of sustaining 0.1 teraops for large problems will be available for deployment by late 1993 and the teraops systems will be available by 1996. Advanced software technology and algorithms will cover scalable libraries, programming languages, and analysis tools for scalable parallel systems in a workstation/server configuration. High performance networking technologies will be produced to satisfy the needs for gigabit networks. These involve interface, protocol, security and multiple types of service over a wide range of performance characteristics. Basic research and human resources will address long term national needs for more skilled personnel, enhancement of education, training, materials and curriculum development in the high performance computing science and engineering areas. Defense specific technologies will focus on special needs for embedded systems such as high density packaging, special accelerators, and realtime fault-tolerant systems.

These will provide a critical edge in performance for broad classes of weapons, command and control systems, and multilayer distributed battle management systems and simulations such as smart weapons with integrated C^3I systems, platforms, or elements of Strategic Defense systems. This initiative will also contribute significantly to civilian applications such as climate ocean, semiconductor, superconductor, and combustion system modeling. Detailed plans for the development of this critical technology are in Annex B, on page 3–1.

4. ***Machine Intelligence and Robotics*** incorporates aspects of human intelligence into computational devices which enable intelligent function of mechanical devices. The principal component fields of this critical technology are:

- Image understanding
- Autonomous planning
- Navigation
- Speech and text processing
- "Machine" learning
- Knowledge representation and acquisition
- Adaptive manipulation and control

These systems will help human operators by functioning as decision–making aids. In the fast–paced battlefield of the future, intelligent machines will fuse, process, and analyze data, and present the results almost immediately. By processing huge amounts of data, machine intelligence can provide more effective tools for effective military intelligence, data analysis, battle management, timely decision–making, and survivability through distribution of tasking, machines, and data repositories. A pilot's associate is being developed which will provide an AI–based decision aid to significantly reduce the information load on military pilots by the turn of the century. In addition, machine intelligence and robotics applications will reduce the need for manpower while improving human response times. Robotics technology involves controlling complex mechanical devices under the direction of computer software in response either to fixed assumptions, or dynamically changing requirements. One example of this type of application is an autonomous robotic ground vehicle or an unmanned aerial vehicle. DoD will demonstrate artificial intelligence for autonomous weapons and vehicles by 2005. When combined with other rapidly advancing critical technologies, such as passive sensors or high performance computing, machine intelligence will provide automatic target recognition capabilities, allow truly effective diagnostic aids, and permit the development of robotic combat systems. First–generation machine intelligence systems already have proven their worth in both defense and commercial applications. Applications of robotics and intelligent machines in manufacturing environments will result in flexible manufacturing capabilities, with shortened setup and production lead times, greater industrial surge capabilities, enhanced quality, and reduced acquisition costs. Detailed plans for the development of this critical technology are in Annex B, on page 4–1.

5. ***Simulation and Modeling***, computer-based, allows the visualization of complex processes and the testing of concepts and designs without building physical replicas. The principal component fields of this critical technology are:

- High-speed graphics
- Solution of non-linear equations
- Simulation verification and validation

Simulation and modeling technology has four major components: computers, networking, visualization, and software. DoD continues to develop advanced capabilities to simulate weapon systems and the tactics which most effectively utilize them as computer capabilities continually increase. This technology can be applied to every major DoD weapon development program to reduce design and production cost, shorten development lead-times, improve performance, improve command and control, and assist in training. By 2001, DoD will attain an order-of-magnitude cost reduction for training and human factors design. For example, training cost effectiveness can be increased by providing a realistic, interactive simulation involving tanks, aircraft, and ground personnel. The payoff for large-scale maneuver simulation, in terms of improved training at reduced cost, is enormous. For example, SIMNET provides a realistic interactive simulation of tanks, armored personnel carriers (APCs), fighter/attack aircraft, helicopters, and other systems. Additionally, in SIMNET newly proposed systems (such as vision devices, antitank weapons, and antihelicopter weapons) can be simulated digitally so that the utility of given technical and human-centered parameter requirements can be assessed before hardware is built. The use of simulation and modeling in the systems design process will enhance the operational suitability and effectiveness of virtually all human/machine systems, whether being initially procured or being modified. DoD is also pursuing battle management simulation technology to evaluate sophisticated systems in hostile environments. Efforts include development of environmental and terrain space technology (including artificial intelligence links to environmental information) , environmental data characterization, and target recognition based on the environment. During FY 1992, the capability to rehearse carrier-based weapon system missions will be demonstrated. As the costs and complexity of hardware development increase, designers in all fields will begin to rely more heavily on modeling and simulation. Computer modeling has significantly affected R&D programs by providing researchers a stronger basis for weapon system design and effects (nuclear, conventional, and chemical) and understanding interactions among low-observables, materials, and geometries with electromagnetic radiation. Detailed plans for the development of this critical technology are in Annex B, on page 5-1.

6. ***Photonics*** is the use of light (photons) for the representation, manipulation, and transmission of information, and includes ultra-low-loss fibers and optical components such as switches, couplers, and multiplexers for communications, navigation, and other information processing applications. The principal component fields of this critical technology are:

- Laser devices
- Fiber optics
- Optical signal processing
- Integrated optics

Photonics technology has long been used in important niches in both defense and commercial applications. But it has been only recently that photonics technology developed the necessary tools and capabilities to bring about revolutionary new applications. By combining fast, massively parallel techniques with devices possessing high spatial resolution, photonics can provide order-of-magnitude improvements over today's conventional electronic devices. Defense photonics will provide currently unavailable capabilities through faster, smaller, more reliable, and more survivable systems. The small size, light weight, and resistance to electromagnetic interference of optical fibers provide major advantages in avionics, microwave, and communications systems, and will see deployment in the defense sector over the next decade. As an example, DoD will demonstrate optical signal processing at a rate of 500 million operations per second by 1996. Over the next 20 years, photonic signal processing devices increasingly will be incorporated into defense sensor, communication, and information processing systems. Photonic processing offers the promise of order-of-magnitude improvements in processing speed resulting from the natural parallel architecture and the high switching speeds of optical devices. By the turn of the century, DoD will demonstrate a 10 gigabit per second local area network. Integrated optics will enhance weapons capabilities in the areas of automatic target recognition, state-of-health monitoring, and detection avoidance. Photonics R &D will significantly affect the high-speed computing defense industrial base through the development of components such as high-speed lasers, detectors, sensors, interconnect media, and signal routing and control elements. Detailed plans for the development of this critical technology are in Annex B, on page 6-1.

7. ***Sensitive Radar*** refers to those radar sensors capable of detecting low–observable targets, or capable of non–cooperative target classification, recognition, and/or identification. The principal component fields of this critical technology are:

- Advanced monostatic radar
- Multistatic radar
- Radars for non–cooperative target recognition and aided/automatic target recognition
- Active phased array radar
- Laser radar
- Electronic counter countermeasures (ECCM)

Radars will continue as a primary sensor since they provide an all–weather capability and do not rely on threat emissions. Continued reduction in target observables will significantly reduce the effective range of existing U.S. surveillance, tracking, target classification, and weapon guidance systems. Sensitive radars (such as large power aperture monostatic radar, synthetic aperture radar, bistatic radar, wideband radar, laser radar, and advanced over–the–horizon (OTH) radar will be required to handle future advanced low observable threats, and to provide needed ECCM capabilities. Advances in radar system components are needed to implement projected sensitive radar improvements. To achieve this goal, by FY 1993 DoD will demonstrate a 50–100 watt (peak), 10 GHz pulsed power transistor. Increasing radar sensitivity creates some significant technical challenges. First, increased sensitivity will require development of frequency generators with increased stability, systems with increased processing gain, and receivers and analog–to–digital converters with wider dynamic ranges. Second, increased sensitivity makes U.S. systems more vulnerable to enemy exploitation, interference by unwanted objects (e.g., birds), and natural phenomena. For phased array radars, DoD's objective is to apply advanced, solid–state distributed active processing and emitter technology, and antenna shapes conformal to mobile platforms. By FY 1992, DoD will demonstrate an 8–inch active array missile seeker which integrates guidance and fuse radar functions. DoD is developing laser radar systems for applications from target detection and tracking to navigation in order to exploit their inherent advantages, increased bandwidth, smaller size, higher resolution. To demonstrate this technology, DoD will prototype a laser radar for obstacle avoidance and target detection by 1996. Sensitive radar technology is a major factor in providing a technical edge to U.S. forces by enhancing detection, localization, classification, identification, and tracking capabilities. Conventional radars are a well–established commodity for military systems, while sensitive radar technologies are still in development and there is only a limited industrial base. Both the conventional and sensitive radar markets are primarily driven by DoD. Detailed plans for the development of this critical technology are in Annex B, on page 7–1.

8. ***Passive Sensors*** do not need to emit signals to detect targets, monitor the environment, or determine the status or condition of equipment. The principal component fields of this critical technology are:

- Passive seekers
- Advanced thermal imagers/IR focal plane arrays
- Infrared search and track sensors (IRST)
- Diffractive optics
- Sensors integration for target acquisition
- Advanced passive antennas
- Passive RF surveillance
- Passive acoustic surveillance
- Fiber optic sensors for environmental and systems status monitoring and navigation
- Superconducting sensors

Passive threat warning technology provides strategic or tactical alert so that defensive measures may be taken. These systems include radar warning receivers, laser warning devices, space-based electro-optic systems, and warning of passive electro-optic/infrared (EO/IR) guided missiles. The latter is particularly challenging and crucial to maintaining U.S. force survivability as heat-seeking missiles proliferate. Infrared search and track (IRST) sensors scan wide areas in order to detect and track air or ground targets. An airborne IRST for use against ship targets will be demonstrated in FY 1993. Advanced acoustic sensors are needed to counter the threat posed by rapid progress in submarine quieting. Multi-band passive electro-optical sensors can reduce the sensitivity of existing sensors to environmental and target signature variations. Integrated sensor approaches will allow for multiple functions and collection of multiple target signatures. Anti-radiation seekers will counter hostile radars and increase the survivability of U.S. forces by targeting enemy radars. A prototype advanced microscan receiver for detecting radiation sources will be constructed in FY 1992. Fiber optic sensors embedded in structures will provide continuous coverage of critical internal variables (like stress and temperature) to evaluate structural performance. The availability of low cost, high efficiency IR sensor technology would find wide application in *in-situ* process monitoring and control, such as real-time temperature monitoring and control of highly temperature-dependent materials refining applications and alloying processes; monitoring and control of temperatures during metal machining, sintering, and composite curing operations; and real-time analysis of chemical processes using time-of-flight laser spectroscopy. Detailed plans for the development of this critical technology are in Annex B, on page 8-1.

9. ***Signal and Image Processing*** technology is the combination of computer architecture, algorithms, and microelectronic signal processing devices for near real–time automation of detection, classification, and tracking of targets. The principal component fields of this critical technology are:

- Algorithm development
- Hybrid optical–digital techniques
- Control of phased arrays
- Artificial neural networks

Application of signal processing technology to weapon systems offers important advantages, such as reducing operator workload, improving system performance, and performing new functions, such as autonomous vehicle control. Perhaps the most immediate enhancements in signal processing and compression can be obtained through the use of new, very–high–performance algorithms, such as compactly–supported wavelet structures and the Gabor transform. Possibly the greatest challenge in signal processing technology is automatic target recognition (ATR), where DoD has a major program underway in algorithm development. The development of advanced ATR capabilities will result in both reduced operator workload and improved system performance. ATR algorithms have been developed for infrared search and track systems which scan for aircraft, and advanced algorithms using spatial temporal techniques will by demonstrated in FY 1992. In reconnaissance and imaging systems, advanced computer architectures will demonstrate new capabilities in the areas of image segmentation, feature detection/extraction, and pattern recognition of static objects. Here, the ability of neural networks to perform pattern recognition is being investigated for synthetic aperture radar, electronic warfare, and anti–submarine warfare. Phased arrays of sensors are electronically controlled through individual activation rather than mechanical steering, while the next technical advance is a conformal array, where the phased array is applied directly to the surface of the vehicle. The demonstration of an airborne conformal array using digital beam steering control will occur in FY 1994. The most important signal processing applications depend on advanced, high–speed, high–throughput processors. Acoustic –array and anti–submarine warfare signal processing share a common technology base and were originally derived from marine seismic techniques for the petroleum industry. The further development of this technology has significant applications to both the military and commercial industrial base, such as the ability to recognize handwritten characters for data entry into computer systems. Detailed plans for the development of this critical technology are in Annex B, on page 9–1.

10. ***Signature Control*** is the ability to control the target signature (radar, acoustic, optical, or other) and thereby enhance the survivability of platforms and weapon systems. The principal component fields of this critical technology are:

- Radar signature (radar cross section) reduction
- Infrared, visual, and ultraviolet signature reduction and management
- Acoustic quieting
- Low probability of intercept radars, communications, and navigation (electronic emission control)
- Deceptive signature (emissions and decoys)
- Magnetic signature control
- Wake signature

The reduction or control of platform signatures greatly improves survivability, resulting in improved weapons effectiveness, while in some cases, the objective is signature enhancement for deception against hostile sensors. This technology area includes the reduction of the wakes created by moving any vehicle through water or air, and by emissions, such as rocket plumes. The reduction of radar signatures is accomplished by vehicle shaping, the use of radar absorbing materials to reduce radar echoes, and passive or active cancellation techniques. For infrared signatures, the reduction is brought about by cooling and/or heating the vehicle or its emissions and by applying special material for background matching to reduce detection by passive systems. In addition, there is a requirement to create low probability of intercept radars, communications, and navigation systems. These programs apply improved spectrum management capability, sensors, and navigation instruments to control sensor emissions to assure C3I and navigation, under low–observability operational constraints. Reduction of the signatures of weapon systems significantly affects their design, support, and effectiveness. Industrial process technologies which are critical to advanced signature control concepts include: computer–aided design and computer–aided manufacturing, computer numerically–controlled machine tools, laser and optical hardware, and robotics. New and improved manufacturing capabilities will be required to transfer new signature control technology materials to system applications that emphasize producibility, cost, and performance. Detailed plans for the development of this critical technology are in Annex B, on page 10–1.

11. ***Weapon System Environment*** incorporates a detailed understanding of the natural environment (both data and models) and its influence on weapon system design and performance. The principal component fields of this critical technology are:

- Ocean characterization and prediction
- Environmental characterization and prediction for path & target area conditions
- Target environment analysis and scene generation

Because of the increasing sensitivity of each generation of weapon system sensors, DoD systems, and strategic and tactical operations are increasingly influenced by natural environmental conditions (e.g., weather, seasons, terrain). The limitations and potential leverage of environmental factors must be clearly understood to increase existing system capabilities and performance, or to optimize the design of new systems. Weapon system environment technology is critical in the selection, development, and operation of superior weapon systems, for such missions as anti-submarine warfare (ASW), "smart" weapons, strategic defense, battlefield surveillance, and communications. For example, DoD will complete a data-driven model for Global Ocean Prediction by 1996. Current smart weapon systems performance degrades under certain environmental conditions. Integration of comprehensive environmental knowledge into the logic modules, design, and testing and evaluation of these systems will increase their effectiveness. DoD will develop integrated environmental simulator scene generation capability for tactical targeting and mission planning. Tactical weapons, as well as strategic defense, requires excellent understanding of the IR background as viewed from surface, air and space. Spinoffs from weapon system environment technology will provide a variety of benefits to the nation. Examples include marine and atmospheric weather prediction for disaster warning, optimal aircraft and ship routing, and the utilization of knowledge of the sea for predicting optimal fishing locations. Remote sensing of the environment will provide insights into crop optimization; improved remote detection and weather prediction capabilities will provide advanced warning of danger over land areas and at sea. Detailed plans for the development of this critical technology are in Annex B, on page 11-1.

12. ***Data Fusion*** incorporates machine integration and/or interpretation of data and its presentation in convenient form to the human operator. The principal component fields of this critical technology are:

- Theoretical foundations
- Algorithm and model development
- Data and knowledge base for fusion processing
- Development of reasoning systems

With the increasing speed and complexity of battle, DoD has recognized the need to integrate data obtained from disparate sensors to yield information about the location, movement, and types of targets. Data fusion technology includes data processing techniques for a wide range of military applications from sensor cueing to cockpit display integration to battle management. This technology will be part of military systems from simple weapons to large-scale information processing applications. As U.S. operational doctrine evolved to stress deep attack and interdiction capabilities, a concurrent demand was created for information describing the location, movements, and intentions of targets beyond the performance of conventional sensors. Programs will be initiated by DoD to meet this demand. To more fully meet the data needs of modern battle management, DoD will demonstrate at-sea fusion of land-based and ship-borne sensor data by 1995. The most complex aspect of fusion technology is dealing with uncertainties associated with data. The evolution of automated correlation and reasoning systems dealing with data and contextual information opens new possibilities for partitioning functions between human and machine, resulting in demonstration of multi-hypothesis reasoning in 1994. DoD research in data fusion will result in improvements to C3I systems by providing the basis for information processing and sensor management which is critical to surveillance activities, advanced "smart" weapon systems, and the design of advanced computer-supported command centers. High-speed, low-cost, reliable techniques for data fusion are of growing importance to automated manufacturing in the defense and non-defense sectors. Real-time process control, sensor-directed cells and workstations, and robot and effector manipulation are three examples of DoD data fusion initiatives aimed at manufacturing products faster and with higher quality. Detailed plans for the development of this critical technology are in Annex B, on page 12-1.

13. ***Computational Fluid Dynamics*** (CFD) is the modeling of complex fluid flow to make dependable predictions by computing, thus saving time and money previously required for expensive facilities and experiments. The principal component fields of this critical technology are:

- Computations of unsteady aerodynamic regimes
- Hypersonic flow solutions
- Turbulence modeling
- Internal flows
- Pre-processing (geometry and grid generation)
- Validation of CFD codes

Because the equations which govern fluid flow cannot be solved analytically, except for the simplest cases, computational techniques are used to solve the equations via numerical procedures on high-speed computers. Of interest to DoD is the ability of CFD to assist in the development of improved flight vehicles, ocean vehicles, air-breathing engines, and weapons including armor and anti-armor warhead design. This technology is a design tool, much like a wind tunnel, to increase the performance and effectiveness of aircraft, ships, missiles, and hypersonic vehicles. As an example, by 1994 DoD will demonstrate full 3-dimensional Navier-Stokes wing analysis, extending to unsteady aeroelastic analysis in 1996. CFD is essential to the design of hypersonic flight vehicles at speeds above Mach 8, where ground test facilities are limited. Additionally, CFD will be used to rapidly identify promising design concepts before wind tunnel tests are conducted, thus significantly reducing system development time. By 1996, the capability to model a complete submarine propulsor system will be demonstrated, assisting DoD in searching for the most effective design configuration. Overarching all of CFD technology is the problem of validation of the codes, recognizing that even the most complex codes are still only approximations. Massively parallel computing architectures and algorithms will produce a huge increase in CFD capabilities over current supercomputers. CFD has proved to be a powerful tool for the U.S. aerospace industry for design modification and problem solving in both military and commercial programs. Its use in the design of next-generation aircraft is expected to help ensure the international competitiveness of the domestic industrial base. Detailed plans for the development of this critical technology are in Annex B, on page 13-1.

14. ***Air-breathing Propulsion*** represents the development of light-weight, fuel efficient engines using atmospheric oxygen to support combustion. The principal component fields of this critical technology are:

- High pressure ratio, lightweight compression systems
- High-temperature, improved life combustion systems
- High-efficiency, highly loaded turbines
- Reduced signature, multi-functional nozzles
- Adaptive, survivable, high-speed integrated control systems
- High-speed, high-temperature mechanical systems
- Operationally realistic, environmentally valid technology demonstrations
- Scramjet combined cycle technology development/demonstration
- Advanced fuels/systems for hypersonic applications

Since their introduction in the 1940s, gas-turbine engines have rapidly evolved, resulting in substantial improvements to performance, fuel economy, and reliability. Turbine engine performance improvements provide the keystone to continued superiority in all DoD aircraft and cruise missile programs, as both upgrades to existing platforms and power sources for new platforms. The Integrated High Performance Turbine Engine Technology (IHPTET) program is a three-phased effort aimed at doubling gas-turbine propulsion capability by the turn of the century. This program aims to advance the technology for turbofan engines (jet aircraft), turboshaft engines (helicopters), and expendable platforms (cruise missiles). Other air-breathing propulsion systems necessary for present and future programs include ramjet/supersonic combustion ramjet (scramjet), combined cycle, and diesel. It is probable that hypersonic propulsion (> Mach 5) will use an air-breathing system, such as a scramjet engine. This high-speed regime poses a new and different series of problems in aerodynamics, engine design, and propulsion/airframe integration. In order to advance propulsion technology, R&D will be required into new materials, reduced signatures, and survivable control systems. These technology developments are leading to "smart engines", which will be capable of actively monitoring and reacting to internal engine conditions to maximize overall performance. Aircraft gas-turbine technology provides militarily superior engines with applications for military and commercial engines, and thus supports domestic competitiveness for the civilian aircraft industry. Advances in materials, design, and aerothermodynamic techniques can be expected to contribute significantly to a wide spectrum of the military and commercial industrial base and continue U.S. preeminence in the air-breathing propulsion technology base. Detailed plans for the development of this critical technology are in Annex B, on page 14-1.

15. ***Pulsed Power*** technology is the generation of repetitive, short–duration, high–peak power pulses with relatively light–weight, low–volume devices for weapons and sensors. The technology encompasses techniques for conversion, storage, pulse–forming, and transmission of electrical energy. The principal component fields of this critical technology are:

- Energy storage
- Power switching
- Conditioning circuits
- Power sources
- High power microwave

Pulsed power technology is required for directed energy weapons (DEW), kinetic energy weapons (KEW), and ground– and space–based identification and surveillance systems. Weapon systems like KEW use hypervelocity projectiles for long–range engagements, and rapid firing rates for anti–missile and anti–armor defense. In addition, pulsed power is also essential for other systems such as laser radars, ultra–wideband radars, and nuclear weapon effects simulators. Energy storage systems often consist of large, high–voltage, high–current capacitor banks that have a modular design. For military applications, energy storage systems must have high energy densities (kJ/Kg) to reduce system weight. In the near term (FY 1992), DoD will demonstrate energy densities to 10 kJ/kg from an inductive system, and in the longer term, DoD will demonstrate energy densities to 1MJ/kg by 1997, thus paving the way for high–performance directed energy weapons. This would also meet the requirements for the most advanced hypervelocity electro–magnetic guns, with velocities of >20 km/sec. Significant improvements are required in opening and closing switch technology for transferring the power from the pulse forming network to the various weapon system loads. This technology requires a high repetition rate using plasma, solid state, and magnetic elements. Detailed plans for the development of this critical technology are in Annex B, on page 15–1.

16. ***Hypervelocity Projectiles and Propulsion*** technology is the capability to propel projectiles to greater-than-conventional velocities (over 2.0 km/sec), as well as understanding the behavior of projectiles and targets at such velocities. The principal component fields of this critical technology are:

- Projectile design
- Projectile propulsion
- Projectile-target interaction

Hypervelocity projectiles provide more penetrating and destructive capability against armored targets, have an increased range, and a decreased time of flight. Applications are anti-armor systems (e.g., tanks, artillery), air defense systems, and theater or strategic missile or re-entry vehicle intercept (both endo- and exo-atmospheric) systems. Propulsion systems that are being investigated include electromagnetic (EM) guns (railguns and coilguns, electro thermal guns, traveling-charge guns with liquid or solid high-energy propellants, hypervelocity rockets, and explosively-driven shock tubes). New designs of armor-piercing, rod-shaped charges, explosively formed penetrators,and long-rod kinetic energy projectiles are also being developed. The X-Rod program is to explore the feasibility of an autonomous or command guided, high-speed kinetic energy penetrator against enemy tanks. DoD will test prototype projectile designs developed in this program in FY 1994. Developments such as reactive armor and complex multilayer armors will significantly reduce the effectiveness of the current antiarmor weapon inventory. The effective range of conventional unguided anti-aircraft projectiles is limited, because targets can maneuver out of the line of fire during the projectile's time-of-flight; however, a hypervelocity projectile's time-of-flight to the target is significantly reduced, thereby increasing the weapon's effective range. For space applications, the Exoatmospheric Thunderbolt effort includes development of a 56 mm EM gun, armature, and power system to achieve high velocity projectile launches, with testing of the prototype system planned for FY 1994. Major R&D efforts exist at the basic and applied research level; therefore, there is little manufacturing capability at this time. Industrial base issues arise from specialized material requirements and small, light, inertial guidance and measurement units. The industrial base is considered sparse because of the lack of maturity and limited size. The potential for commercial spin-off of EM gun technology is in the plating and welding area. Detailed plans for the development of this critical technology are in Annex B, on page 16-1.

17. ***High Energy Density Materials (HEDM)*** are compositions of high-energy ingredients used as explosives, propellants, or pyrotechnics. These compositions contain high-density stable explosive compounds, binders, plasticizers, and other energetic ingredients, such as metallic compounds. The principal component fields of this critical technology are:

- Explosive applications
- Propellant applications
- Warheads
- Chemically bound,excited state components
- Nuclear isomers

These materials may be able to release up to 10 times the energy now stored in current explosive materials and propellants. This is a field of high risk research and speculative payoff. HEDM propellants provide the means of getting most ordnance items to the target, and once near the target, provide the means to kill the target. The breadth of systems that will benefit from HEDM range from strategic missile propulsion, to mines, to conventional warheads, explosives and propellants. While increases in energy-density are continually sought, other important parameters include safety, stability, signature, toxicity, and reliability. One objective of the development program is advanced warhead design with higher lethality to compensate for increased miss distances, and to allow smaller warheads, more propellant, and longer ranges. For tank armor, a 50% increase in penetration thickness is sought, greatly increasing the vulnerable area of the enemy tank. A significant technology development effort is underway to reduce the signature of tactical missiles, reducing the danger of observation for the attacker. The goal is to develop a propellant with no visible signature and a factor of ten reduction in infrared signature. To meet these goals, DoD, DoE, and industry research programs must encompass scientific programs in combustion, detonation physics, reaction kinetics, and synthesis of new materials. The industrial base for HEDM provides its products to DoD, DoE, and NASA. Most non-military applications are related to satellite launch systems, NASA and commercial space customers, and commercial blasting agents. Detailed plans for the development of this critical technology are in Annex B, on page 17-1.

18. ***Composite Materials*** are defined as two or more constituent materials that are combined together in such a manner as to produce a substance possessing selected properties superior to those of its individual components. The principal component fields of this critical technology are:

- Polymer (organic) matrix composites
- Metal matrix composites
- Carbon matrix composites
- Ceramic matrix composites
- Hybrid composites

Composite materials possess high strength, low weight, and are able to withstand high temperatures for aerospace and other applications. Composite materials technology promises significant improvement for weapons performance, design, and affordability. For some systems, composites are recognized as the enabling technology required for fulfillment of demanding thermal, structural, and mechanical requirements (such as for the National Aero Space Plane (NASP), advanced gas turbines, deep submergence vehicles, spacecraft, ground combat vehicles, and long range cruise missiles). The major objectives for this technology are to: (1) develop alternative materials and manufacturing processes that provide composites and components with improved performance at acceptable cost to meet DoD mission requirements; (2) incorporate concurrent engineering, design, and producibility into materials and manufacturing processes; and (3) develop a focused mechanism for transitioning and supporting new composites rapidly into production applications. Metal matrix composites (MMCs) are an important emerging technology. DoD's development of MMCs will result in a demonstration of matrices for high thermal conductivity and high temperature applications by FY 1992. Composite materials will be needed to make future systems most effective in a wide spectrum of vehicle structures, including high-temperature propulsion systems, hypervelocity vehicles, short take-off and landing (STOL) and vertical take-off and landing (VTOL) vehicles, as well as for spacecraft, protection against directed energy threats, and advanced hull superstructures and forms and submarine structures. Composite materials offer the potential to provide lighter systems that are more agile and deployable than are possible with conventional approaches. By 2001, DoD will demonstrate a 25 to 50% weight reduction in airframes, land vehicles, and space vehicles. In addition, DoD is developing damage-tolerant composite materials and hardening concepts for protection of platforms and weapons systems against operational hazards and advanced threats. Military demand for high-performance materials in the United States is projected to maintain a thriving community of advanced materials and equipment suppliers. At present, advanced materials developed for military applications are expensive relative to the commercial sector. Detailed plans for the development of this critical technology are in Annex B, on page 18-1.

19. ***Superconductivity*** This technology makes use of the zero resistance property and other unique and remarkable properties of superconductors for creation of high-performance sensors, electronic devices and subsystems, and supermagnet based systems. The principal component fields of this critical technology are:

- Low temperature superconductors (LTS)
  - Supermagnets
  - Sensors and electronics
- High temperature superconductors (HTS)
  - Supermagnets
  - Sensors and electronics

Introduction of superconducting devices offers the potential for reducing drastically the energy losses and cooling requirements, which in turn make for much improved processing speed and packaging density in digital microcircuitry. The frequency selectivity in analog filters using superconductor elements can not be approximated by other types of devices. The recently discovered high-temperature superconducting materials offer further decreases in cooling requirements, promising the use of liquid nitrogen, rather than helium as a coolant, which makes potential applications much more practical. The challenge in the field is how to make the best possible (relatively near-term) use of the well established technology of low-temperature devices (operating at less that 23°K) while resolving the serious problems associated with the use of high-temperature superconductors, which in the long-term may be more promising.

The DoD LTS program covers electric drive system for ships, electric generators, magnetic energy storage systems, electromagnetic guns and catapults, microwave and millimeter wave generators, analog communication and surveillance system components, and digital electronic subsystems and systems, including analog-digital converters, cross-bar switch, cache-memories and digital signal processors. Many of these LTS developments will endure, but they will also serve as prototypes for later HTS applications which use transition temperatures as high as 125°K or possibly above. While the HTS devices impose lesser refrigeration penalties, problems of brittleness, crystalline anisotorphy, corrosion and bulk current density still require extensive development. The DoD plan for HTS materials aims at the fundamentals in the development of bulk conductors for magnets, thin-film sensors and electronics, together with the associated manufacturing processes.

Superconductor applications will result in higher performance sensors and electronics for the military and reduced weight, volume and power requirements. Electromagnetic propulsion of ships and projectiles may become practical through the introduction of HTS devices. Detailed plans for the development of this critical technology are in Annex B, on page 19-1.

20. ***Biotechnology*** is the systematic application of biology for an end use in engineering or medicine with many potential defense applications. The principal component fields of this critical technology are:

- Processes
- Materials
- Sensors

Because of the discovery and exploitation of biological mechanisms that control living organisms, it is now possible to engineer microbial, plant, and animal cells to act as factories for the synthesis of existent or new materials at substantially enhanced rates and efficiencies. Biosynthesis of new enzymes, which are biological catalysts, offers the prospect of developing new pathways for synthesis or degradation of chemicals. The DoD is constantly pressing the forefront of materials technology, both because of the severe working environments and the need for extremely high reliability. Biotechnology may offer an attractive means for producing new classes of materials, at low cost, with the added strategic advantage of using non–petroleum–based feedstocks. The cost of developing some new materials is also likely to decrease when they are produced biologically because of the potential for producing "generic" materials that may be easily modified at the molecular level without the need to develop a new manufacturing scheme. Biosensors have extremely high selectivity and sensitivity, exceeding anything obtainable by non–biological sensors. The objective of the DoD sensor effort is to discover the basic principles used by living–system sensors and exploit them in designing new sensors. Advanced, antibody–based sensors for real–time detection of chemical and biological agents will be demonstrated in FY 1993. Bioprocesses have the intrinsic advantage of requiring far less energy and therefore can be considerably less costly. They are also less environmentally damaging and proceed with greater speed, specificity, and selectivity than do conventional processes. Additionally, recombinant DNA technology can be used to tailor organisms to perform specific tasks or to manufacture products that would be difficult or costly to obtain using conventional methods. Basic research efforts in decontamination technology are aimed at developing generic approaches to design of enzymes for catalytic degradation of broad classes of chemical warfare agents. There is a great need to be able to develop enzymes rapidly and inexpensively that will exhibit high activity for new chemical agents. FY 1995 is the target for meeting this goal. Testing of protective coatings and camouflage creams using existing enzymes is expected to be completed by FY 1993. This effort has been accelerated significantly during 1990 to meet the demands of the Persian Gulf War and a number of new materials will be produced in FY 1991. Detailed plans for the development of this critical technology are in Annex B, on page 20–1.

21. ***Flexible Manufacturing*** is the integration of production process elements aimed at efficient, low cost operation for small, as well as high volume part number variations, with rapidly changing requirement for end product attributes. Manufacturing involves people, equipment, materials, information, and controls acting together to transform materials into products. The principal component fields of this critical technology are:

- Product data definition for automated manufacturing
- CAD/CAM/CAE/CAPP
- Databases and database management
- Communications and networking
- Intelligent software interfaces

One of the key merits of flexible manufacturing is the ability to operate efficiently at variable production rates, to expand rapidly and efficiently to higher output levels, to accommodate reasonable changes in the output product specifications. Success hinges upon the reliable insertion of automated and flexible information (storage, processing, and retrieval) into the translation of design concepts, engineering, detailed designs, and the many diverse mechanical and other processes involved in manufacturing. The DoD technology development plan comprises standards for definition of product data, design of integrated computer aided design–engineering–manufacturing process planning and control, data management, and communications.

The impacts on DoD's future are seen as increased ability to accommodate, at affordable cost, the rapidly changing needs for prototyping, small production runs, and potential expansion to large–volume production. Changes in the manufacturing processes, caused by introduction of new design specifications or improved materials will be accommodated without expensive redesign of the whole manufacturing process. Industry will benefit from the standardization implied by the DoD program so that the diverse computer aided processes will be increasingly compatible and adaptable to integration at the single, and perhaps the multi–plant, levels. The need for upgrading personnel skills in order to achieve the best possible task distribution between human operators and production equipment will be addressed by both DoD and industry developmental activities. The training of semi–professionals in designing and operating highly automated systems will also benefit. Detailed plans for the development of this critical technology are in Annex B, on page 21–1.

IV. FUNDING OF DEFENSE CRITICAL TECHNOLOGIES

The development of advanced defense technologies requires predictable levels of investment and program support, but also the flexibility to make rapid adjustment when needed. DoD's investment strategy is thus designed to provide a strong, sustained approach to technology development. DoD's support for the Defense Critical Technologies reflects this consistent, long-term commitment.

Tables 2A and 2B in Chapter I provide a summary of estimated DoD funding for the Defense Critical Technologies in the FY 1987–91 period, as well as annual totals for FY 1992–97. These figures present funding from the DoD Science and Technology program and include the Strategic Defense Initiative Organization (SDIO), as well as a summary not including SDIO.

DoD research and technology efforts are managed as programs. In fundamental research, funds tor specific technologies are generally readily identifiable. As research comes closer to application, the focus changes to programs that combine and integrate technologies to produce items of military utility. Cost accounting programs in DoD are geared to tracking program costs and are not well suited to tracing costs to technology areas. Further, military critical technologies by definition impact a wide range of applications. Details of the funding of Critical Technologies by program element are shown in Annex A.

DoD is planning for incremental, consistent, long-term increases in emphasis for S&T funding relative to other parts of the RDT&E program. Figure 2 shows that DoD S&T, and especially funding for critical technologies, fare well in light of the programmed reductions in Defense RDT&E (shown here without SDI funds). Projected S&T funding will grow from 16% of total DoD RDT&E in the President's FY 1991 request to more than 22% of RDT&E in FY 1997. During this same period, critical technologies funding increased from 8% to 12% of the total DoD RDT&E. It should be noted that these percentages are understated because classified funding is not included. This demonstrates the commitment we have made to keeping our S&T program strong.

Figure 3 illustrates that funding for critical technologies grows significantly as a fraction of S&T, whether or not SDI funds are a part of the picture. In particular, critical technology funds (excluding SDI) increase from approximately 37% to 52% of S&T. Of particular note is the emphasis on critical technology support over the last year as shown in the following table of budget requests and Congressional funding.

	FY 1991 Request	FY 1991 Congressional Funding	FY 1992 Request
Critical Technologies as % of S&T (without SDI)	37%	50%	52%
Critical Technologies as % of S&T (with SDI)	30%	41%	35%

Budget Requests and Congressional Funding Ratios

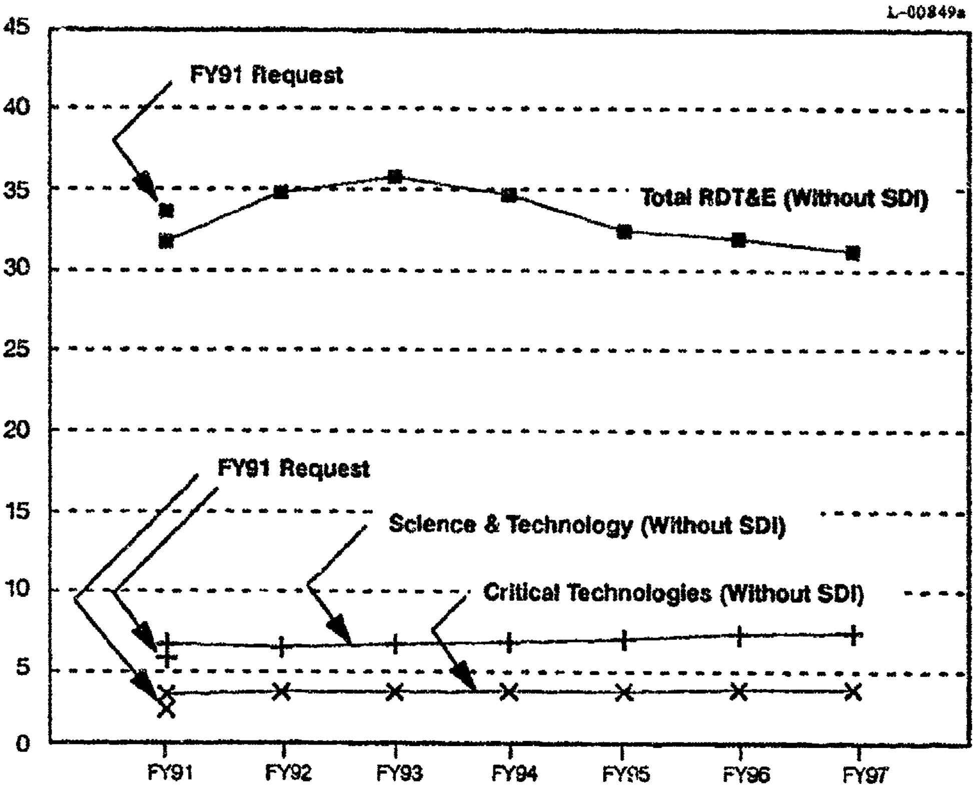

Figure 2 DoD RDT&E, Funding ($ Billions)

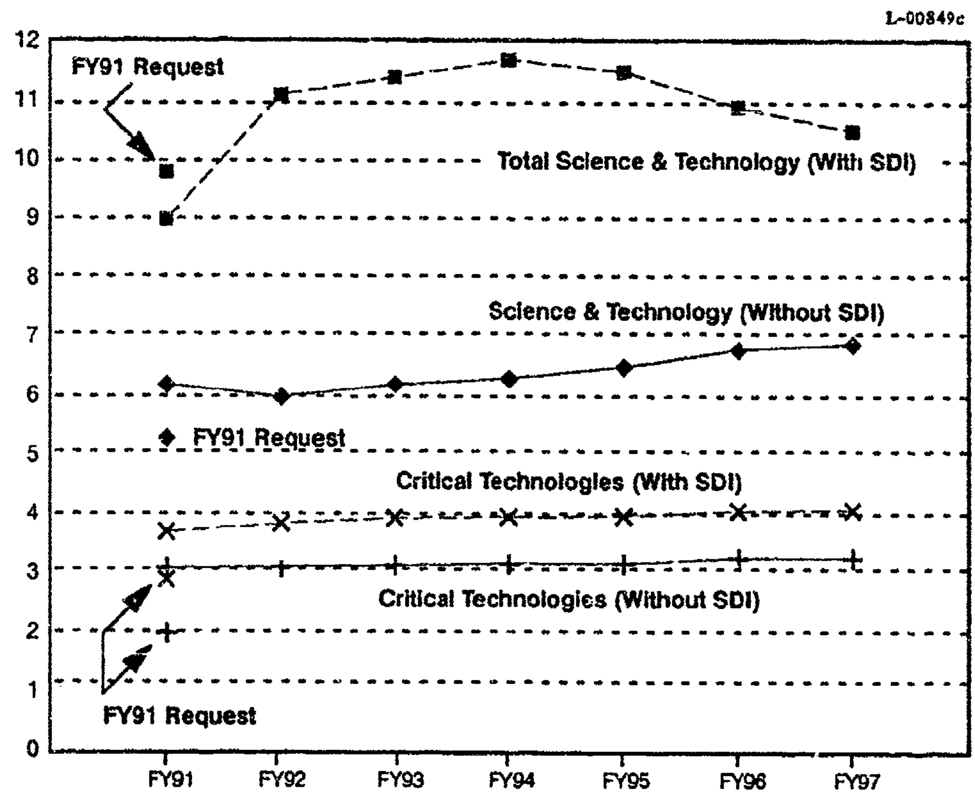

Figure 3 DoD Science & Technology Funding ($ Billions)

For FY 1992, the resources for Service-executed evolutionary technology developments will be better managed because of the outcome of the Defense Management Review (DMR). Resources are also adequate for breakthrough, revolutionary technologies, with DARPA taking the lead and with contributions from the Services, the Department of Energy laboratories, and industry. Funding needs for trump card technologies are more difficult to characterize. Our goal in this arena must be to foster an environment that allows and rewards discovery and invention of those new basic science and engineering developments on which trump cards depend, while fostering high-level management sensitivity in DoD and the military for their importance and potential.

In line with the White House initiative on High Performance Computing and Communications, the Defense Critical Technologies Plan contains $232 million for DARPA (as compared to the FY 1991 base of $183 million) to pursue technical objectives associated with high performance computing, such as systems, network technology, and enabling software. This initiative, which is being coordinated by the Federal Coordinating Council for Science, Engineering, and Technology, is a balanced program to extend our nation's leadership in high performance computing and computer communications; to put those technologies to work for defense as well; and to make these technologies an integral part of science, technology, and industry. This is an example of the sort of high-leverage breakthrough opportunity we can capture with the right guidance and resources.

Our overall budget is sound, but we will reexamine opportunities and priorities for FY 1993 budget refinements and guidelines pertinent to the 1994–1999 FYDP. The full impact of our planning will be felt in FY 1994, as we continue to evaluate our priorities during the PPBS process and increase emphasis on higher priority programs, using the framework provided by the Defense Critical Technologies Plan and by further analysis of technical opportunities and new user needs.

V. MANAGING SCIENCE AND TECHNOLOGY

The objectives of the DDR&E for the DoD S&T programs are:

1. To ensure a strong S&T program that uses to the full all available technical opportunities to meet the DoD users' needs;

2. To ensure that the S&T programs of the DoD are adequately resourced, with fully adequate resources devoted to the most important objectives, and with the lesser needs funded on an austere basis;

3. To ensure that the S&T programs are well managed by the performers, and that the technical output of the S&T programs are well utilized by the users.

The Defense Critical Technology Plan (DCTP) is an important management tool for achieving these objectives. In particular the DCT planning process will be used to provide a clear statement of the S&T program to the DoD Planning, Programming, and Budgeting System. This Statement will be made in terms of technical objectives, of improvements in military capabilities to be obtained from the use of the technical results, and of the resources required to achieve the technical results.

The technical program objectives and the desired improvements in military user capabilities will be set by the DDR&E, with the assistance of the Deputy DDR&E(R&AT), and the Defense Science and Technology Steering Group. The Services, Defense Agencies and others will make their contributions through the DS&T Steering Group.

The Defense Critical Technology planning process will provide continuous improvement for the S&T performers by involving military users and outside technical helpers as needed.

The DCTP and the DCT planning process will contribute importantly to the Acquisition process. They will do so primarily by providing a detailed but highly structured description of S&T program objectives. This will assist the DAB committees in evaluating the technical risk of DAB programs. Another contribution will come from the highly skilled cadre of technical experts, managers, and planners assembled by the DS&T Steering Group.

THE DEFENSE CRITICAL TECHNOLOGIES PLAN OF 1991

ANNEXES A AND B

ANNEX A
CRITICAL TECHNOLOGIES FUNDING BY PROGRAM ELEMENT

ANNEX A
CRITICAL TECHNOLOGIES FUNDING
BY
PROGRAM ELEMENT

Tables A-1 and A-2 provide the funding for the critical technologies in each of the applicable program elements in the DoD Science and Technology program for the fiscal years 1991 and 1992 respectively.

The Defense budget is arranged into a large number of program elements (the number of program elements in the DoD Science and Technology programs is 160 in 1991 and 153 in 1992). Each program element is broken down into a number of units, sub-units, etc., usually ranging from projects to tasks. Each program element represents a cohesive technology area containing many related activities.

Some program elements support generic technologies, but most are focused on developing improved military capability and thus encompass a number of technology areas. (For example, a program element dedicated to improving surveillance and detection on the battlefield might include optical, infrared, radar, and seismic technologies.) In addition, funds for basic research are allocated by discipline (such as mathematics, computer science, physics, electronics, biology, etc.). The funding in Tables A-1 and A-2 was developed by determining the extent to which the individual tasks were contributing to the development of one or more of the critical technologies.

ANNEX B
CRITICAL TECHNOLOGIES DETAILED PLANS

ANNEX B
CRITICAL TECHNOLOGIES
DETAILED PLANS

This Annex provides a comprehensive review of each of the 21 Defense Critical Technology Plans. The purpose of these plans is to provide both policymakers and technical personnel with a concise, yet complete and readable, roadmap for each of the Defense Critical Technologies. These summary plans should clarify technological issues and therefore contribute to an informed policymaking process.

The individual technology plans are the product of a lengthy coordination process involving the combined efforts of the Military Services, Defense Agencies, the Office of the Secretary of Defense, the Department of Energy, and three National Laboratories to assess and identify those technologies seen as critical to the "long term qualitative superiority of United States weapons systems," and to set forth plans for their timely development. Valuable inputs and comments were received from the Defense Science Board, the National Science Foundation, the National Aeronautics and Space Administration, and the National institute of Standards and Technology. We especially appreciate the detailed and careful review of last year's plan provided by three industry associations, the Aerospace Industries Association, the Electronic Industries Association, and the National Security Industry Association. All these inputs contributed greatly to making this a better document.

A. Selecting Critical Technologies

The Critical Technologies were selected on the basis of the criteria listed below. Major improvements in one or more selection criteria are sought.

Performance Criteria

- Enhancing performance of existing weapons systems
- Providing new military capabilities

Quality Design Criteria

- Contributing to availability, dependability, reliability
- Contributing to weapon systems affordability (lower life cycle cost through producibility, maintainability, etc.)

Multiple-Use Criteria

- Pervasiveness in major weapon systems
- Strengthening the defense industrial base.

The selection process started with a consideration by a group of technical experts, representing all major DoD and DoE components sponsoring science and technology activities, of numerous candidate critical technologies. Each candidate critical technology was broken down into "technology sets" which were further refined by including (or excluding) specific technical activities. Each candidate critical technology so defined was measured against military payoffs and the selection criteria listed above. This year's selection process had the advantage of two years of experience, plus the benefit of other critical technology planning efforts (such as ones by the Defense Science Board, by the National Critical Technologies Panel chaired from the Office of Science and Technology Policy, by the

Department of Commerce, and by industry associations such as the Aerospace Industries Association). Since their selections are remarkably similar, our process this year concentrated on refining last year's selection (leaving most of the critical technology titles unchanged, but making some changes among the technology sets); adding one new technology concerned with the integration of other technologies for manufacturing (Flexible Manufacturing).

A further refinement in the selection process involved assessing the pay-off of the critical technologies in a wide range of military applications. A matrix method was developed by the group of experts with the active participation of the Joint Staff. This method permits the assessment process to be carried out in stages, cascading from National Security Objectives through various intermediate prioritization matrices to (finally) critical technologies. (The intermediate stages represent recognized entities such as Basic Force Packages, and Mission Areas.) In this way each stage of the assessment may be carried out by the most knowledgeable personnel, for example starting with military planners and ending with technologists. The systematic participation of such a diversity of experts gives this method added credibility.

B. Organization of the Technology Plans

This annex contains a detailed plan for the development of each technology. Each plan is organized as follows:

- *Description of Technology*: A brief, narrative description of each critical technology.
- *Payoff*: The impact of anticipated technological advances upon the capabilities of future weapon systems and on the industrial base is discussed. A discussion of the impact of technology development on logistics is included in this year's plan.
- *S&T Program and Plans*: This section provides a summary description of each plan. To provide the necessary level of detailed planning information, the elements of the plan are presented in terms of the components of the critical technology, which are divided into "technology sets," which in turn are subdivided into "technology activities." (Each CT averages about 25 such activities.) Objectives are set for the coming budget period (6 years), and technology development milestones are projected up to a 15-year time horizon.
- *Leveraging Industrial Base Capabilities*: Current and projected industrial base capabilities are addressed in this section. The section draws heavily upon the recently completed DoD Report to Congress on the Defense Industrial Base: Critical Industries Planning, 1990.
- *Related R&D in the United States*: Technology development plans of NASA, the National Science Foundation, and NIST are incorporated here along with summaries of private sector efforts.
- *International Assessment*: Foreign technological capabilities are compared in this section. A new feature, added this year, describes technology trends for nation or groups of nations which have comparable technological capabilities to the United States. This section also summarizes existing technology exchange agreements and international cooperation.

1. SEMICONDUCTOR MATERIALS AND MICROELECTRONIC CIRCUITS

1. SEMICONDUCTOR MATERIALS AND MICROELECTRONIC CIRCUITS

A. DESCRIPTION OF TECHNOLOGY

Since its inception three decades ago, microelectronic circuit technology has been responsible for the creation of dozens of new industries such as data processing, home computers, robotics, software, and video games. It has fundamentally altered communications, education, health care, recreation, entertainment, and work activity. For the soldier in the field, it has extended the range his eyes can see and his ears can hear. Microelectronic circuit technology has expanded the ability of his brain to make timely decisions on a technologically complex battlefield and multiplied the muscle power he can deliver against an enemy. Because microcircuit technology has affected a wide range of diverse industries and capabilities, it is considered critical to the future of our national economy and our national security.

Microelectronics technology involves phenomenal reductions in the size of complex electronic circuits. Today, these reductions have made possible complete computer chips that are no larger than a fingernail. Shrinking electronic circuit feature size results in the ability to achieve greater circuit densities (circuit elements per area). For example, technology advances have quadrupled the storage capacity of dynamic random access memories (RAM) every 3 years over the past 20 years. Other important benefits achieved with shrinking electronic circuit size include lower power demand, higher reliability, lower cost, and very high speed.

While microelectronics technology not only strives to make circuit features smaller, it also works to increase their complexity. This increase in circuit complexity requires extremely high quality semiconductor materials and sophisticated equipment that can make patterns that are smaller than the wavelength of visible light. It requires dimensioning gate lengths that are smaller than a millionth of a meter and measuring the thickness of surface coatings in molecular diameters. A typical microcircuit requires hundreds of separate manufacturing steps, each of which must achieve a near perfect reliability to allow a cost-effective yield of the final device. These sensitive devices must be designed (and then must be properly packaged) so that they can withstand rugged military environments and be able to tolerate high levels of radiation.

This critical technology includes the investigation and characterization of a variety of new semiconductor materials that offer the potential for significant performance increases and cost reductions. It encompasses the development of new manufacturing methods and tools to produce quality wafers from which circuits can be built. Microelectronic circuitry technology is also concerned with developing a wide range of technologies that are necessary to produce highly advanced microelectronic circuits. These technologies include:

- Computer-aided design (CAD) techniques that allow designers to creatively manipulate constantly increasing amounts of complex circuitry, extend current practice into the system-to-chip design concept, and significantly reduce the design time.
- Far-term, high-risk lithography technologies such as electron beam (E-beam), excimer UV, x-ray with both proximity and projection systems, and ion beam.

- Fabrication technologies that capitalize on industry practices but focus on military needs such as low-volume manufacturing, radiation hardening, and extended temperature range devices.
- Packaging and interconnect technologies that enhance circuit performance and prevent degradation.
- Advanced materials such as diamond, silicon carbide (SiC), and indium phosphide (InP) that offer advantages over gallium arsenide (GaAs) and silicon (Si) for high-power operation and better thermal management.
- Technologies that improve the overall quality control and thermal management of microelectronic circuits.

For purposes of description, the components of microelectronics fabrication may be divided into: *wafer preparation technologies* (the technologies, equipment, and processes used for mass production of semiconductor wafers, including crystal growers, slicers, polishers, and preliminary dopant equipment); *epitaxial growth technologies; wafer fabrication technologies* (the body of processing technologies used to fabricate integrated circuits on prepared wafers); *design technology* for mask making; and *packaging, assembly, and test technologies*.

Specific defense-related research and development plans in this Critical Technology are directed toward fulfilling a wide variety of vital defense applications. Current research and development thrusts range from development of full manufacturing processes to exploration of promising (though perhaps novel) specialized techniques or applications. A representative list of defense-related R&D thrusts currently underway includes efforts supporting advances in analog/digital device production; power converter device production; development of novel artificial neural networks (using analog signal processor circuits); high resolution lithography technology (especially using x-ray and excimer optical techniques, among others); development of processes for very large scale integration (VLSI) technologies (with contributions from SEMATECH); and radiation resistant isolation, especially SOI material development. The table below summarizes these representative technology sets.

Technology Sets in Semiconductor Materials and Microelectronic Circuits

- Very large scale integrated circuits
- CAD for complex circuits
- High resolution lithography
- Analog/digital converters
- Power converters
- Micro- and millimeter wave sources and amplifiers
- Transmit/receive modules and arrays
- Signal control components
- Radiation-hard isolation technology

Silicon-based semiconductor technology is highly advanced and continues to provide the bulk of conventional integrated circuitry and high-power devices. The dominance of silicon-based semiconductor manufacturing technology will continue for a decade or more.

Thus, long-term DoD/DoE efforts in microelectronics technology can be expected to significantly involve silicon technologies for the indefinite future. In fact, advances in silicon-based technology continue at an impressive rate, continuing to make it difficult for alternative technologies over the near- to mid-term to compete in digital electronics.

Microwave and digital GaAs technology is expected to become competitive with silicon-based microelectronics in the long term and promises significant advantages over comparable silicon-based devices for selected military applications. For example, GaAs has an electron mobility nearly seven times higher than silicon and inherently better resistance to radiation damage than does silicon. Thus, a GaAs integrated circuit may eventually be faster and lower power than a silicon-based counterpart of similar design and complexity. Also, unlike silicon, gallium arsenide has a direct bandgap, thus permitting a wider range of potential applications (e.g., in optoelectronic devices). However, GaAs today remains inferior to silicon in some radiation problems (such as single-event upset for space radiation).

GaAs and other compound semiconductors such as InP and indium gallium arsenide (InGaAs) play important roles in microwave and millimeter-wave devices and circuits. Other materials such as indium antimonide and mercury cadmium telluride are used for infrared and optical detection. None of these compound-semiconductor technologies are nearly as developed as Si technology, which has benefited from more than two decades of substantial research and development.

InP devices offer higher voltages and electron velocities than those made of GaAs or Si, and InP laboratory prototypes have demonstrated three times the power capability of GaAs devices. SiC devices promise to be even better in these respects than InP devices, and, in addition, can operate at elevated temperatures up to at least 500°C. Diamond technology shows the greatest promise because of its superior thermal conductivity and electronic properties. Electronic devices made of diamond ultimately should be unsurpassed for high-power, high-temperature applications as well as applications demanding radiation hardness.

B. PAYOFF

1. Impact on Future Weapon Systems

a. Weapon System Performance

Microelectronics technology has a pervasive effect on virtually every U.S. weapon system, current or future. Increasing miniaturization techniques allow major modifications of current weapons platforms (such as the creation of aerodynamically unstable aircraft controlled by onboard microprocessors, as on the F-16) to the development of radically new weapons concepts (e.g., "brilliant" weapons). The ability to build in self-test circuitry will greatly reduce maintenance problems and improve overall systems reliability. Microelectronics technology may critically affect operations scenarios and deployment tactics by providing ever increasing decision aids and communications capabilities between tactical/theater commanders and their battlefield assets.

Increasing circuit complexity and functionality also will allow major expansion of key military operational capabilities for reconnaissance, surveillance, and target acquisition (RSTA); command, control, and communications (C^3); and battlefield lethality. For example, the envisioned availability of gigabit (10^9 bits) dynamic random access memory (DRAM) will increase information access to large data bases by three orders of magnitude or more, possibly as early as 2000 to 2005.

The technology sets described in this plan contribute substantially to realizing the defense-related potential of this Critical Technology. For example, Analog/Digital Converter efforts emphasize developing devices with higher sampling rates and increased bit resolution. Such devices can be used in nearly all DoD weapon systems to substantially increase this performance; Power Converter efforts help enable such devices to be packaged in the confined spaces of weapons and systems; Artificial Neural Networks are an example of a promising longer term approach to increasing existing computational speeds by 100 to 1,000 times; High Resolution Lithography efforts which emphasize imaging or projection optics provide vital development of a critical manufacturing process and technology; VLSI/ULSI efforts support advanced production of all types of integrated circuits, both military and commercial; and new radiation hard isolation technologies, such as SOI material for the fabrication of radiation hard microelectronics.

Silicon-based microelectronic technology will continue to prevail during the very high-speed integrated circuit (VHSIC) era and for the foreseeable future. At the same time, GaAs will remain the most readily available and commonly used material for microwave and millimeter-wave frequency devices and circuits. In the longer term, indium phosphide may emerge as the material of choice for applications requiring high RF power. These circuits are critical building blocks for DoD electronic warfare, radar, smart and brilliant weapons, and communications systems. The high performance, potentially low cost, unit-to-unit reproducibility, and inherent radiation hardness of GaAs circuitry make it very useful in front-end analog functions in these systems. GaAs also shows promise in solid-state active aperture antennas (phased arrays). In the 1990s. GaAs integrated circuit elements will appear more frequently in equipment for communications, electronic warfare, electronic intelligence, avionics, missile guidance and control, and surveillance from space.

Future weapons systems will rely even more upon devices made available by advances in semiconductor design and fabrication techniques. The ability to design and integrate new microelectronic components into weapons systems is an essential corollary to device fabrication technology. Our future defense posture relies in part on our ability to rapidly exploit advances in microfabrication technology to design and produce devices for use in military systems.

b. Logistics Infrastructure

In the manufacturing process, DoD consumes lower volumes of custom-designed products than the typical commercial sector user. DoD products have fewer developmental and/or operational test hours before rigid design/configuration constraints are imposed. Logistics demands for this technology include support of efforts to rapidly identify and resolve hardware malfunctions within normal sustaining engineering and maintenance support functions. Future microcircuit technology advances should emphasize prognostic- and self-diagnosis, reconfiguring abilities, time/performance/stress measurement and logging capabilities, and environmental feedback which is built into the chip designs.

Rapid changes in microcircuit technology are escalating the microelectronic device obsolescence problem exponentially. The challenge for the logistics infrastructure is to keep pace with microcircuit technology advances and growing device complexity, while still being able to acquire or manufacture replacement spares. The design and manufacturing life cycle is two to five years, while the weapon system support cycle is measured in decades.

New capabilities to rapidly emulate obsolete microcircuits with qualified design and manufacturing processes are urgently needed for replacement spares. Obsolete, out-of production microelectronic devices are frequently needed as spare components in operational systems for as long as 10 to 20 years after the microcircuit manufacturing and board-level production facilities have converted to new technologies. As new DoD systems rely on greater numbers of ASIC devices, the impact of parts obsolescence will grow.

Advanced product development and description support tools, integrated from microcircuit to system, must be developed and acquired by both the design and support communities to ensure that product configurations are upwardly compatible over the support life cycle. Extensions of hardware description languages to the analog domains (low and microwave/millimeter-wave frequency) are essential. Development of integrated tool frameworks that permit the automated transfer and application of product descriptions across development, system emulation, and product testing domains is needed. Further, rapid qualification of processes and components requires the same product and process description languages and tools. The overall logistics infrastructure goal is to achieve dramatic cost avoidance in long-term support of systems.

Rapid design and manufacturing changes require rapid advances in test, diagnosis, and troubleshooting capabilities as well as standards for automation. Advances in system-level architecture and simulation must be achieved in order to assure supportable system designs before the manufacture of expensive custom devices. DoD must use these future simulation capabilities to ensure first-pass development and manufacturing of supportable systems. Reprocurement will require accurate design representations, similar to and built on the foundation of the VHSIC Hardware Description Language (VHDL), for use throughout the support cycle.

2. Potential Benefits to Industrial Base

a. Manufacturing Infrastructure

The thrusts toward ultra levels of miniaturization and higher speeds of operation are clearly applicable across a broad front of domestic electronics technology and will continue to benefit many industry sectors and the consumer. Most military-oriented semiconductor technology developments are directly applicable to the domestic industrial base. For example, the recently completed VHSIC program has had many direct, immediate beneficiaries, including the computer, automotive, telecommunications, and robotics industries. It is difficult, however, to identify any domestic segment that would not be affected, directly or indirectly, by advances in semiconductor technology, whether based upon silicon or gallium arsenide. Differences between military and commercial development often involve DoD requirements for certain, specific levels of radiation hardness, degree of ruggedness, and perhaps higher frequency and power millimeter-wave capability. SEMATECH, the semiconductor manufacturing technology consortium of U.S. industrial firms with some DoD support, has the potential to contribute to the U.S. technology base and competitiveness in the worldwide semiconductor industry. SEMATECH's efforts are directed toward making the United States a world leader in future submicron silicon technology. The major thrust of SEMATECH includes the development and enhancement of the semiconductor equipment industry and materials supply base.

DoD efforts in GaAs and InP technologies will also affect industrial development of future microelectronic materials and devices. High-speed GaAs circuits and specialty infrared sensors are beginning to find commercial markets. High-speed GaAs processors are being used in next-generation supercomputers. High electron mobility transistors are also being used in television receivers. GaAs, aluminum gallium arsenide (AlGaAs), and strained-layer (Ga,In)As transistors are also being used in television receivers. Longwavelength lasers (constructed from epitaxial layers grown either strained or lattice-matched to InP) will significantly impact communications. High-performance detectors for these longer wavelength systems are available. Optical interconnects for integrated circuits potentially can provide very high-volume, high-speed chip-to-chip and processor-to-processor communication for a variety of computing and data storage applications.

b. Logistics Infrastructure

Increased reliability and self-diagnosing, healing devices will reduce the frequency of repair functions and, therefore, depot repair demands.

Line-replaceable units will be expensive to replace and repair. Since DoD acquires microelectronics rather than manufacturing them in-house, defense industry needs to ensure the availability of sustaining manufacturing capabilities that are automated, flexible, and reconfigurable over system implementation life cycles. DoD also needs the flexibility to target manufacturing to the most economical process for compatible form, fit, and function (F3) replacement parts. This flexibility can only be achieved based on standardized hardware descriptions.

In addition, depot maintenance and repair capabilities must be selectively upgraded to handle advanced technologies and materials and remain compatible with commercial manufacturing capabilities. Specialized repair facilities for procedures such as debonding/rebonding of microelectornic chips in multi-chip packages and modules will remain with the manufacturer over the near term. Life cycle maintenance and support requirements must address long-term depot needs.

New standards and architecture constraints for both the weapon systems and the supporting test equipment should be developed to ensure compatibility between new technologies and future support environments. By developing these standards, DoD will make the defense industrial base more flexible and, therefore, more competitive.

New development and design tool environments, based on the standard DoD language Ada, are needed to ensure long-term supportability and sustainability of products. These environments must support the automated capture of electronic product model information, translation and development of required test strategies, and automated test program generation capabilities.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Very Large Scale Integrated Circuit (VLSI) Technology

(1) Objective

Development of new material systems that offer significant improvement in performance and cost. Development of new manufacturing technologies including large volume and flexible manufacturing.

(2) **Development Milestones**

- FY 1992 — Demonstrate SiGe heterojunction-bipolar-transistor logic
- FY 1993 — Demonstrate SiC circuits and diamond coatings for improved thermal management
- FY 1994 — Demonstrate production (0.35 micron) device technology
- FY 1995 — Demonstrate 16K SRAM C-HIGFET devices made of AlGaAs/GaAs and InAlAs/InGaAs
- FY 1996 — Demonstrate non-volatile memory to replace magnetic disc, e.g., floating gate, ferroelectronic technology

b. **CAD for Complex Circuits**

(1) **Objective**

Extension of current computer-aided design capability to encompass system-to-chip design and advanced packaging. Exploit the success of the VHSIC Hardware Description Language (VHDL).

(2) **Development Milestones**

- FY 1991 — CAD for 100 x 100 synapse array
- FY 1993 — CAD for 10 million transistor synapse array
- FY 1996 — Achieve chip-to-system computer-aided design capability
- FY 1997 — Demonstrate CAD tools tha[illegible]rpc[illegible]ate advanced packaging techniques

c. **High Resolution Lithography**

(1) **Objective**

Develop new lithographic techniques, including 193-nm optical lithography and x-ray lithography, and the required industrial base capability for volume production of integrated circuits with feature sizes in the 0.1–0.3 μm range.

(2) **Development Milestones**

- FY 1991 — Demonstrate synchrotron aligner
- FY 1992 — Demonstrate prototype 193-nm excimer laser lithography system and resist technology
- FY 1993 — Availability of 1x production mask capability for proximity x-ray

- FY 1994 — Commercial availability of production-worthy 193-nm optical lithography systems
  — Demonstration of compact synchrotron capability
- FY 1995 — Prototype x-ray, electron-beam, or ion projection lithography systems

d. Analog/Digital Converters (ADCs)

(1) Objective

Develop silicon-based analog-to-digital converters with higher sampling rates and increased bit capability to achieve greater processing speeds and accuracy, and radiation hardened for specific applications.

(2) Development Milestones

- FY 1991-Demonstrate 14-bit, 25-mega-sample per second ADCs
- FY 1993-Demonstrate 16-bit, 125-mega-sample per second ADCs
- FY 1995-Demonstrate 10-bit, 1 Giga sample per second ADCs.

e. Power Converter Technology

(1) Objective

Develop highly regulated, low-voltage power converters with increased power densities and higher efficiencies.

(2) Development Milestones

- FY 1993 — Demonstrate 95 percent efficient, 100W-250W, 100W/cu.in. power converters.

f. Microwave and Millimeter Wave Solid State Sources and Amplifiers

(1) Objective

Develop three terminal III-V compound devices for operation in 44, 60, and 94 GHz systems. Emphasis is on efficiency, power, frequency, noise figure, bandwidth, small size, low weight, affordability and reliability.

(2) Development Milestones

- FY 1992 — Demonstrate advanced heterojunction bipolar transistors
- FY 1993 — Demonstrate pulse power transistors for mm-wave-radar
- FY 1994 — Demonstrate InP power high temperature microwave devices

- FY 1995 — Demonstrate monolithic integrated circuits operating up to 100 GHz
- FY 1996 — Demonstrate silicon carbide power devices
- FY 1997 — Demonstrate diamond power devices
- FY 1997 — Demonstrate solid state amplifier producing 5w at 50GHz

g. Transmit/Receive Modules and Arrays

(1) Objective

Develop high reliability, solid state, transmit/receive (T/R) modules and arrays for multimode radar; wideband arrays for radar, ECM, and ESM; advanced IC designs for transmit/receive modules; 20, 44, 60 and 94 GHz airborne and space arrays. Emphasis is on higher module efficiency, broad bandwidth, low sidelobes with adaptive null placement, beam agility, low radar cross section, reliability, and affordability.

(2) Development Milestones

- FY 1992 — Demonstrate array filtering techniques
- FY 1994 — Demonstrate 40 GHz T/R module
- FY 1995 — Demonstrate 60 GHz T/R module
- FY 1996 — Demonstrate 40 GHz multibeam active phased array
- FY 1997–Demonstrate wafer scale integration for phased arrays

h. Signal Control Components

(1) Objective

Develop surface acoustic wave and acoustic change transport filters, compressors, and correlators. Develop switches, limiters, phase shifters, broad band planar mixers, circulators, and frequency synthesizers. Emphasis is on higher power, broad bandwidth, small size, low noise and loss, high yield, hardened and reliable devices.

(2) Development Milestones

- FY 1992 — Demonstrate 8–18 GHz miniature ferrite circulators
- FY 1994 — Demonstrate 30–100 GHz planar control components
- FY 1995 — Demonstrate ICs incorporating microwave, optical, and digital functions
- FY 1996–Demonstrate low loss phase shifters (1–100 GHz)
- FY 1997–Demonstrate 100 GHz EW frequency synthesizer

i. Radiation Hard Isolation Technology

(1) Objective

Develop ultra large-scale integration technology with advanced isolation methods using silicon-on-insulator (SOI) substrates with advanced radiation resistance (total dose, transient upset, single event upset and neutrons). Utilize the static random access memory as the technology demonstration vehicle. Emphasis is on low-cost, defect-free SOI wafers in diameters ranging from 100-200 mm.

(2) Development Milestones

- FY 1993–Demonstrate rad-hard, 1 M-bit, CMOS, SRAM on SIMOX material
- FY 1994–Demonstrate high speed, rad-hard, BICMOS, SRAM on SIMOX (< 10 nsec access time)
- FY 1996–Demonstrate radiation-hard 0.5 micron CMOS/SOI, low volume processing technology using SOI isolation
- FY 1997–Demonstrate large diameter, low cost, defect free, SOI material (< 10^2 CM^{-2} defects, 10^{10} cm^{-2} impurities, 200–250 mm wafers)

  Demonstrate mega RAD total dose hardness at liquid nitrogen temperature

2. Technology Objectives

The table on the following page summarizes the DoD technology objectives in the area of microelectronic materials, circuits, and their fabrication.

3. Resources

A summary of total S&T funding[1] is shown in the table below.

Funding — Semiconductor Materials and Microelectronic Circuits ($M)

FY87-91	FY92	FY93	FY94	FY95	FY96	FY97
1,955	479	481	487	488	490	510

4. Utilizing the Technology

Silicon-based digital and analog integrated circuits are widely used throughout DoD weapon systems and communication systems and platforms. In fact, an important objective of the DoD VHSIC program was to accelerate the fielding of products created by advanced semiconductor production technology by accelerating component insertion rates. This pervasive use of silicon-based integrated circuits will continue for the indefinite future.

[1]Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

Technology Objectives – Semiconductor Materials and Microelectronic Circuits

Technical Area	By 1996	By 2001	BY 2006
Electronic circuits, including VHSIC, providing highly reliable and radiation-hardened technology	• 0.5 micron low-volume production available in digital silicon devices • Improved bulk and SOI technologies	• 0.2 micron low-volume production of digital silicon devices/SOI	• Less than 0.1 micron production of low-volume digital silicon devices
Millimeter and microwave integrated circuits providing reliable analog capabilities for system front-ends	• Continuous increases in single function (amplifiers, oscillators, mixers, switches) chips available in 1 to 20 GHz range	• Integrated multiple function chips available over entire 1 to 100 GHz range • CAD/production facilities available to meet large range of system requirements • Heterojunction MIMIC	• Microwave/digital integrated circuits • Microwave/optical integrated circuits
Computer-aided design tools	• Continued test/reliability/process design on advanced parallel computers • Fast prototyping of continued circuits	• Testable, complex designs generated by scalable design tools • Rapid prototyping to second-level packaging	• Fail-safe, fault-tolerant, self-repairing adaptivity inherent in microelectronic subsystems
Manufacturing	• Expanded qualification procedures for gate array microcircuits	• National quality procedures for micro-electronics available • MMST	• Wafer scale integration for high-volume production
Fabrication of compound semiconductors	• Mass production of 4-inch diameter, 25 kg boules for GaAs substrates • Continued progress on improvement of MOMBE and MOCVD single wafer deposition equipment • Development of reliable sources of InP wafers	• Production of 5-inch diameter GaAs substrates • Production of high quality, 3-inch diameter InP substrates	• Production of 6-inch diameter boules for GaAs substrates
III-V integrated circuits (e.g., GaAs)	• Complementary logic • Improved medium-scale integration gate arrays	• Large-scale integration complementary logic circuits in production	• III-V integrated circuits fully compatible with silicon-based circuits
Materials Development	• SOI for 0.35 μm ICs • SiC • Diamond on Si	• SOI for 0.2 μm ICs, 3-D structures • SiC manufacturing • Diamond ICs in labs • InP manufacturing	• SOI in <0.1 μm ICs • SiC ICs • Diamond ICs • InP ICs

DoD's microwave and millimeter–wave monolithic integrated circuit program is focused on the development and production of affordable, reliable analog circuits for use as sensors and signal processors in the front–ends of electronic warfare, radar, smart munitions, and communication systems. These circuits, fabricated primarily from gallium arsenide, operate at frequencies from 1 to 100 GHz. Devices being used include GaAs metal–semiconductor field effect transistors (MESFETs), high electron mobility transistors (HEMTs), and heterojunction bipolar transistors (HBTs).

Rapid insertion of electronic device technology into weapon systems is needed to ensure continued defense system superiority. Technology options to fulfill this need primarily involve new and more encompassing CAD techniques. In this regard, the VHSIC hardware description language (VHDL) used in the design, specification, simulation, and test of microcircuits has been adopted as an international standard. The VHDL design concepts are being expanded beyond the chip level and will encompass system level requirements. VHDL will have a positive impact on speeding up the use of microcircuit technology.

D. LEVERAGING DOMESTIC INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

Microcircuit technology currently is dominated by silicon–based manufacturing processes. Manufacturers often use silicon in microcircuits whose minimum feature size is 0.7 microns and less. These microcircuits are fabricated from wafers cut from boules of silicon grown to as large as eight inches in diameter. A large percentage of microcircuits in current weapon systems applications are customized parts, called application–specific integrated circuits (ASICs). DoD and commercial silicon manufacturing processes are essentially identical, but DoD applications tend to select devices produced by stricter physical standards of ruggedness. Existing manufacturing issues in silicon for both DoD and the commercial sector include lithography processes and packaging and CAD for high–complexity circuits.

GaAs technology is rapidly expanding and in the next decade may make significant inroads in the analog IC market. At least 27 US companies have GaAs programs. DoD has made a significant GaAs investment through the $225 million MIMIC program. The primary objective of MIMIC is to reduce the cost of monolithic microwave integrated circuits, and it addresses such critical areas as CAD, assembly, and test. The cost of MIMIC chips has been reduced from $20 per mm^2 to $4 to $8. Eighty MIMIC chip designs have been completed and half of these have been fabricated with yields as high as 93 percent. Progress is also being made in digital GaAs manufacturing. Three pilot production lines have achieved record quality levels for digital GaAs, and a variety of technology insertion efforts are underway.

2. Projected Industrial Capabilities

In order to be competitive, U.S. silicon IC manufacturers must develop the capability to make deep submicron ($\leq 0.35\mu$) VLSI/ULSI circuits using wafers larger than eight inches. This will require extensive investment in capital equipment, CAE and CAD, materials research, etc.

While significant progress has been made in GaAs raw material, challenges remain to achieve high–volume, low–cost manufacturing. One challenge is the uniformity of the epitaxial layer (which is critical to device performance and yield). Techniques such as metal–organic chemical vapor deposition (MOCVD), metal–organic molecular beam epitaxy (MOMBE), and molecular beam epitaxy (MBE) are being developed and refined. While MBE provides good control, it is a slow process. To improve throughput, techniques and equipment are needed to provide for simultaneous epitaxial growth on multiple wafers. DoD has initiated a manufacturing technology program to develop the technology for a 6–inch, 20 kg boule. Inherent in this program is the effort to control the growth of the boule to produce a more uniform wafer. Development of nondestructive evaluation (NDE) techniques is also required to support high–volume production. These techniques, such as on–wafer characterization of circuits, are essential to provide real–time data for automated statistical process control. Many of these advancements will also apply to silicon. Other contemporary DoD manufacturing technology investments supporting and utilizing this critical technology include: improving the yield of semiconductor materials for high–performance seekers and sensors used by missiles and target acquisition systems; automating hybrid circuit production; establishing processes to produce replacement integrated circuits that are no longer in production but are still being used in DoD weapon systems; and working toward a flexible microelectronics manufacturing system.

Commercial independent research and development (IR&D) funding is significant in the microelectronic area, but with the rapid pace of technology development and increasing complexity and sophistication of semiconductors, it is increasingly difficult for a company to fund the efforts to implement all of these advances. To help maintain a robust U.S. industrial base in this critical technology, industry, government, and academia have established cooperative efforts. Semiconductor production equipment is very expensive and may become obsolete in a few years after it is introduced. DoD microelectronics manufacturing S&T efforts include developing a flexible microelectronics manufacturing system for application–specific ICs having in–situ sensors, expert system process control, and single–wafer processing.

Objectives — Industrial Base (Manufacturing Capabilities)

	By 1996	By 2001	By 2006
Material	• Wafer quality (GaAs) • SOI material (200 mm) for <0.35 μm ICs	• SOI material (250 mm) for <0.2 μm ICs	• II–VI/III–V material suitable for nano–electronics • Processing IC MOMBE • Wafer quality InP
Fabrication and assembly	• Circuit emulation (Si) • Automation • Multichip packaging	• Cluster tool processes • X-ray lithography	• 3–D circuits • Integrated cluster tool processing • Data driven/integrated manufacturing
Test and inspection	• Multi–dimensional x-ray inspection • Holographic inspection	• Z-plane inspection on wafer testing • Electro–reflective inspection	• Sensor–based manufacturing

E. RELATED R&D IN THE UNITED STATES

U.S. research work involves all major facets of the technology, with special emphasis on cost–reduction bottlenecks (such as clean–room practices and equipment and high–throughput lithography) and new miniaturization techniques (such as 3–D scaling processes).

The bulk of this research is applied to development of commercial microcircuits. While much commercial R&D has direct military input, and vice versa, only about 7 percent of the semiconductor market in recent years has been related to military sales. As a result, issues of importance to DoD fabrication technology (such as radiation hardening) usually have not been emphasized as heavily in commercial technology. This difference may be disappearing, however, as many of the affected processes and tools find increasing applications in each sector.

1. R&D in Other Agencies

The Department of Energy has a research program in fabricating epitaxial thin films and developing new devices in semiconductor materials. The program encompasses all phases necessary for the realization of new devices, from epitaxial film growth through device design (and fabrication) to testing. Devices under development include ICs and optoelectronic devices. This work includes a strong effort in strained layer materials systems to determine their advantages in modern devices, e.g., lasers, transistors, and detectors, as well as research and development of technologies for the radiation hardening of silicon integrated circuits. The materials growth and device research and development program is supported by substantial theoretical work, experimental materials studies including growth and characterization, and development of in-situ diagnostic techniques. DoE programs include improvements in photolithographic sources such as laser produced x-rays, synchrotron sources, and advanced free electron lasers.

A program at the National Institute of Standards and Technology (NIST) develops measurement tools for use by the electronics industry in the manufacture of semiconductor devices and integrated circuits; provides measurement methods, reference data, standard reference materials, and mathematical models; conducts research in semiconductor materials, manufacturing processes, discrete devices, and integrated circuits; and integrates experimental and theoretical work to provide a solid basis for understanding measurement-related requirements in semiconductor technology. Research activities include basic investigations of the theory and behavior of materials and structures, improvement of measurement methods to characterize materials and devices, metrology and artifacts for the manufacture of integrated circuits, and the development of special circuits used in characterizing the performance of transistors.

The National Science Foundation (NSF) also conducts semiconductor materials and microelectronic circuit research, and provides strong linkages among universities, industry, and government. The NSF supports investigator-initiated research that advances our understanding of semiconductors and semiconductor devices, and that opens new technologies or revolutionizes existing technologies. Research is supported in such areas as compound semiconductor materials synthesis; material and device characterization; lithography (optical/UV, ion/electron beam, x-ray); and VLSI design.

Three NSF centers have research activities related to semiconductor materials and microelectronic circuits: the Center for Quantized Electronic Structures, the Center for Compound Semiconductor Microelectronics, and the Center for Advanced Electronic Materials Processing.

2. R&D in the Private Sector

The U.S. private sector continues to conduct significant levels of R&D in silicon-based technology development. Industry R&D investment rates can be as high as 25 percent or more of company sales. U.S. R&D in GaAs and InP preparation technology is still largely supported by military investments, but commercial investment is now increasing as the technology becomes a stronger competitor to existing silicon-based microelectronics. Currently, GaAs R&D investment is not nearly as extensive as is existing silicon-based R&D, but most major US semiconductor firms have at least some efforts underway.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

U.S. industry dominated the worldwide semiconductor market from the late 1960s. Its leadership, however, suffered a constant erosion by other industrialized countries (primarily Japan). In 1986, the U.S. lost world market share leadership. Future trends indicate continued market share declines. Closely coupled with this market share decline is the decline of the semiconductor materials and equipment industry that supports semiconductor manufacturers. These problems are being addressed by the SEMATECH program.

While the United States has lost its world manufacturing leadership position, it is still generally recognized as the world technology leader. However, since manufacturing, and ultimately sales, generates the revenue for R&D, the future of U.S. technology leadership is somewhat questionable. The implications of the decline in technology and manufacturing leadership for the DoD include the potential for foreign dependence in this critical area and increase the possibility that advanced microcircuit technology may be made available to our potential adversaries. Many U.S. semiconductor companies have formed partnerships with Japanese and European firms.

Still, the U.S. microelectronics industry today leads the USSR in semiconductor and microelectronic R&D in virtually every area of significance. The USSR remains limited in its ability to close the microelectronic technology gap due to a variety of processing difficulties and systemic problems.

Soviet work in GaAs microelectronics has been a longstanding adjunct to their microwave device R&D. While they have some capability to produce high-quality GaAs, they are believed to lag substantially in their ability to apply the material to devices in volume production.

The table on the following page provides a summary comparison of the United States and other nations for selected key aspects of the technology. Ongoing international R&D indicates potential international capabilities to contribute to meeting the following challenges and goals:

- ULSI (< 0.3 micron) feature size
- Implementation of Bi-CMOS and GaAs MIMIC circuits
- Bulk or epitaxial growth of compound semiconductor materials
- Radiation hardening.

Japan is believed to be ahead of U.S. efforts in GaAs integrated circuit fabrication techniques. Japan's capabilities in GaAs materials and circuit fabrication could make significant contributions to U.S. capabilities and the needs of the Western alliance. Japan also is active in InP materials development.

Summary Comparison — Semiconductor Materials and Microelectronic Circuits

Selected Elements	USSR	NATO Allies	Japan	Others
VLSI/VHSIC < 0.3 micron features size	□	□□	□□□□ ○	
Implementation of Bi-CMOS and GaAs MMIC circuits	□	□□ [b]	□□□□ ○	□□ Israel
Bulk or epitaxial growth of compound semiconductor materials	□□ [b]	□□□ [b] ○	□□□□ ○	□□ Israel
Radiation hardening	□□ [b]	□□ [a]	□□□ [a] –	
Overall[c]	□	□□□ +	□□□□ ○	□□ Israel

[a] Basic contribution from circuit design/fabrication advances and in GaAs materials

[b] Limited quantity high-quality GaAs materials

[c] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

- □□□□ broad technical achievement; allies capable of major contributions
- □□□ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
- □□ generally lagging; allies may be capable of contributing in selected areas
- □ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

- \+ Foreign capability increasing at a faster rate than the United States
- ○ Foreign capability increasing at a similar rate to the United States
- – Foreign capability increasing at a slower rate than the United States

In terms of VHSIC-related fabrication at very large scale integration (VLSI) levels, Japan now dominates in memory device manufacture, and in most aspects of microelectronics manufacturing, with the exception of ASICs. The existence of 0.5 micron VHSIC pilot production lines in the US represents a world leadership position. It is expected that the Japanese will surpass this capability within the next few years.

The US maintains a worldwide lead in microprocessors, but the Japanese are making a dedicated effort to narrow the gap. They are pursuing a more open architecture designed to support a real-time distributed processing operating system. Indicative of Japanese advances is the announcement of a 64-bit microprocessor chip with basic features similar to US products.

Our NATO allies, individually, do not presently rival either the United States or Japan. However, this situation could drastically change in the near term. The European countries have extensive capabilities in a number of important niche technologies. The formation of such joint efforts as the European Strategic Program for Research in Information Technology (ESPRIT) and the Joint European Submicron Silicon Initiative (JESSI), coupled with the planned economic unification of Europe in 1992, can only be expected to enhance the integration and effectiveness of these existing capabilities.

The ESPRIT program is active in the area of Bi-CMOS, and the UK, France, and Germany have developed some significant capabilities in the area of GaAs. These NATO countries are also actively pursuing other advances in silicon-based technologies. JESSI (present participants include companies from Germany, France, the Netherlands, and Italy) hopes to extend the consortium's capability in design systems, materials, and fabrication to the 64 million bit DRAM level (4 million bit DRAM level using SOI technologies). With regard to certain underlying niche technologies, these activities have considerable potential for cooperation. In terms of the supporting technologies for fabrication of VLSI/VHSICs, Britain's Science and Engineering Research Council has announced important advances in E-beam technology that possess significant potential for submicron lithography.

Within NATO, a number of companies have active research programs in GaAs and indium phosphide (InP). The UK is reported to have developed a unique design architecture for GaAs digital filters. France appears to be the front runner in promoting and using GaAs devices, and several other NATO countries are reported to have active programs including Germany, the Netherlands, and the UK.

Canada has an active program in CAD and basic material research. Canada is reported to have developed a CAD program that accurately calculates a number of parasitic effects, of particular interest in the development of higher density MIMIC devices.

The following countries possess capabilities slightly behind, equal to, or slightly ahead of the best US capabilities and could contribute to meeting future US technology challenges:

- UK: Strong in crystal growth, E-beam lithography, and E-beam diagnostic equipment. A major U.S. firm (IBM) has reportedly entered into a contract with a UK firm to purchase compact synchrotrons for x-ray lithography.
- Germany: Strong in silicon crystal growth technology, metallization equipment, x-ray lithography. Germany is also reported to be pioneering the use of differential molecular-beam epitaxy for the fabrication of stacked ICs.

- Netherlands: Strong in chemical-vapor deposition (CVD) and E-beam lithography.
- Switzerland: Strong in die bonders, mask blanks, and thin-film deposition.
- Israel: Strong in CAD and aspects of compound semiconductor materials processing.

In addition, the Republic of Korea is making significant progress and is reported to have the capability to produce VLSI devices with 1.25 micron or finer feature sizes. While the Republic of Korea appears, for the present, to be drawing on U.S. and Japanese technology, it has the resources and the potential to pursue innovative efforts in the near future. The same appears to be true, but perhaps to a slightly lesser degree, of Taiwan and Hong Kong.

Of interest is the number of European researchers who believe that GaAs will not prove to be the last word in high-speed semiconductor materials. Specifically, InP is believed to offer higher radiation resistance, with higher purity (99.99999 percent claimed) and better fabrication repeatability than GaAs. This approach is being actively pursued by France and several German firms. Also indicative of significant capability in this technology is a French effort in complex GaAs/GaAlAs and InGaAs/InP structures for integrated optics. Israel is also believed to be making progress in the processing of compound semiconductor materials.

2. Exchange Agreements

There is a high level of exchange activity in the area of microelectronics between the United States and free world countries. U.S. participation in NATO programs in physics and electronics and optical and infrared technologies provides a mechanism for exchanges of fundamental scientific information in underlying technologies of semiconductor materials and devices.

The Technology Cooperation Program (TTCP) provides a vehicle for a range of applicable exchange activities in basic semiconductor materials, microelectronic devices, and electro-optic materials and devices.

Each of the Services also has exchange programs with NATO and other friendly nations in areas of specific interest. These exchanges provide a mechanism for technology sharing in a wide spectrum of materials and device fabrication technologies, including electro-optics and millimeter wave and microwave technologies applicable to processing of compound semiconductor materials and integrated circuit fabrication. Examples of Service programs illustrating the breadth of activity include programs in microelectronics and their applications with France and Germany and programs in electro-optics and infrared technology relevant to compound semiconductor materials and devices with France, Germany, Italy, Spain, and some non-NATO nations.

2. SOFTWARE ENGINEERING

2. SOFTWARE ENGINEERING

A. DESCRIPTION OF TECHNOLOGY

Software has become the focus of functionality and flexibility in most large-scale military and commercial systems. While the DoD is now producing and supporting software systems involving millions of lines of code, the costs and risks associated with the management of these systems are high. And, in spite of the scale and power of these systems, the true potential power and flexibility of software is still largely untapped. It is this power and flexibility, however, that multiply the challenge of creating a true software engineering discipline supported by an evolving and flexible tool base.

Technology Sets in Software Engineering

- Software and system engineering processes and environments
- Real-time and fault-tolerant software
- Reuse and re-engineering
- Software for parallel and distributed heterogeneous systems
- High assurance software

These areas span the range of the major software technology challenges addressed by DoD. The technology of software and system engineering environments includes process and associated tool support for all phases of the software lifecycle, from requirements formulation through design, development, testing and evaluation, rework, deployment, logistics, repair, re-engineering, and reuse.

Many defense systems, particularly weapon systems, involve an interconnection of sensors, communications, decision-making, and generation of control signals. Software for these systems, which usually involve multiple interlinked computers, often must be assured to meet time constraints and to perform despite faults or failures in the interconnected physical systems. Engineering and management for these time-critical realtime systems involves assuring that performance criteria are met in a wide range of circumstances and faults.

In most engineering disciplines, there is an enormous amount of reuse of prior experience, represented through engineering standards, conventional process models, building-block components, standard test structures, documentation conventions, domain-specific and generic tools, and other kinds of shared assets. Software assets can include, for example, interface definitions, domain-specific architectures, software components, test cases, and specification components. An effective reuse regime can enable a component-oriented approach to development and management of large scale software systems. Reuse technology includes software component definition and composibility technology, software asset libraries, and techniques for the re-engineering of existing system components.

High performance computing systems of all kinds, including scientific/engineering systems, embedded systems, and the leading edge information systems, make use of heterogeneous parallel and distributed computer system configurations. Systems software, including operating systems, databases, and communication support, must support mixed configurations with high performance in a flexible, secure, and robust manner. As systems software becomes more powerful and interfaces converge to standards, hardware configurations will become increasingly flexible, enabling major performance and function upgrades late in the lifecycle of a system.

Defense software, including both weapon systems and information systems, often has very stringent requirements for assurance of consistency of system implementation with safety or security requirements. Security requirements can include, for example, confidentiality, integrity or authentication. Safety requirements generally assure that a system will not enter a hazardous state. Safety and security, and other kinds of critical requirements, must be supported by process and technology that can provide high levels of assurance of correct behavior.

The scale and intensity of DoD's needs in these mission–critical software areas goes well beyond the corresponding needs and available software technology in the commercial sector. DoD's challenges include both creation of the necessary software technology and stimulation of its availability in broadly–supported, non DoD–unique commercial products.

B. PAYOFF

1. Impact on Future Weapon Systems

a. Weapon System Performance

Software is a key element of virtually all major defense systems. Software development and maintenance costs in DoD are estimated to be as much as 10 percent of the entire DoD budget. Because of the critical role that software plays in system functionality, deficiencies in software affect overall system performance out of proportion to the software development and maintenance costs.

The increasing allocation of system functions to software offers the important advantages of reduced system replication cost as well as the flexibility to adapt to changing system requirements and system "smarts" that are limited only by the cleverness of the software designers and the power of the underlying computing platforms. These are fundamental advantages of software, and they are the reason why increasing amounts of system function will be embodied in software regardless of improvements in other technology areas.

Improvements to the software engineering process and associated tool and environment support yield improvements in cost, schedule, quality of product, and predictability of process. Software engineering tools provide a kind of "force multiplier" for system and software developers, enabling more powerful systems to be developed and supported.

In addition, with conventionalization to common architectures and interfaces, transition can occur to a management approach centered around components and subsystems rather than lines of code. With these larger building blocks, more powerful and flexible systems can be constructed.

Most weapon systems that include embedded computing may employ multiple sensors and operator inputs, with the sensor and input data processed to determine system actions, which are then effected through various control systems, which may include display screens to support interaction with human operators. Software provides the fabric that links together these activities, and it is in the software process that it must be assured that time–constraints and deadlines will be met in the expected range of inputs. In addition, the software cannot be brittle. When sensors or control systems fail or provide false readings, the software must be sufficiently fault tolerant to continue operation, even if at a somewhat degraded level.

With software controlling so many weapon system functions, it is through software assurance technology that many critical systems properties are assured, such as security from penetration attack, security from probes, and safety of operation.

b. Logistics Infrastructure

Software adaptation and upgrade often offers the most cost-effective means to enhance performance and functionality for existing systems, including currently fielded systems. For this reason, post-deployment rework, system evolution, and maintenance account for approximately 70 percent of the total software development and maintenance costs cited above.

It is therefore essential in new system developments to address adaptability and lifecycle considerations directly. A small increment in development costs can yield a very large reduction in downstream costs. As cost and metric data are gathered, it will be more effectively possible to assess these tradeoffs in the early stages of design, enabling a more rigorous approach to design for adaptability.

With the changing defense environment, defense capability improvements are more likely to arise from enhancements to existing systems and less likely to arise from new developments. In addition, the range of threats is proliferating, and the extent of interoperablity requirements is changing rapidly. Because of this, systems need to be engineered in a more flexible way. Software offers the most effective and flexible means both for design/re-engineering upgrade and for subsequent logistic support. As the commercial market for computing technology continues to grow, DoD exploitation of commercial capabilities will become even more important in system design, resulting in systems that may have both DoD-supported and commercially supported components.

Progress in each of the five critical areas of software engineering will have a significant impact on the software aspects of weapon systems logistics. Software and system engineering environment technology will facilitate a more component-oriented approach, enabling a software component-by-component system upgrade. Software environments will also maintain design records from earlier phases or from reuse repositories, reducing the need to reverse engineer existing software systems prior to adapting them. Use of a system design record supported by very fine-grained configuration management can drastically reduce costs associated with upgrade through the narrowing of the focus of test and evaluation efforts required for acceptance of the enhanced system.

Adherence to conventionalized architectures and interfaces will enable support organizations for existing systems to exploit improvements made by others in shared system components, thus spreading the enhancement costs among multiple system organizations.

2. Potential Benefits to Industrial Base

a. Manufacturing Infrastructure

In software technology, as in many other areas of computing technology, DoD has had and will continue to have an enormous effect on the industrial base, well out of proportion to the extent of DoD research and development investment. DoD R&D investment, when effectively managed, has a significant catalytic effect on the industrial base, including both commercial and defense industry, with the result that DoD can more often exploit commercial developments in support of its mission needs.

Past DOD R&D investment has led to major impacts on the U.S. computing technology industrial base, including, for example, timesharing, parallel computing, COBOL, Ada, network operating systems including Unix, technology for security, the mouse, packet-switched networking, and other technologies now part of the computing mainstream.

In each of these areas, technology and market risks were sufficiently high that mainstream commercial investment was very limited at the time DoD became involved in the technology. The DoD investment was made in order to accelerate the rate at which technologies would become available to meet DoD mission needs. In areas where the appropriate investment policy was to catalyze commercial development, a spin-on effect resulted, enabling DoD to exploit downstream commercial market growth and free itself of a requirement to subsidize the full costs of continued technology growth. Another critical area of early DoD investment is in activities that can lead to new standards. By catalyzing standards efforts, DoD can accelerate availability of a capability required to meet its mission needs.

Indeed, areas of computing technology investment where the DoD has not been successful are those areas where it has built an entirely DoD-specific technology base, such as with the many service-specific programming languages in use prior to the introduction of Ada. Because there was no commercial acceptance of these languages, DoD was forced to bear the full costs of sustaining the technology base for each of these language systems throughout the lifecycles of all systems dependent on those languages. Similar pitfalls exist for DoD-specific operating systems and programming environments. This is why, for example, current DoD environment efforts are focused on developing compatible commercially-supported frameworks that can support evolving commercial software engineering tools.

Because of the proliferation of the technology, the computing and software technology market share attributable to DoD is shrinking. Because DoD has even more stringent and aggressive software requirements, it is essential that DoD continue to work with the commercial market catalyzing emergence of technologies to exploit through spin-on. This will ensure that downstream DoD needs will be met, that they will be met in a cost-effective manner, and that the commercial base will gain through the accelerated introduction of new software technologies.

In the future (as with the past DoD R&D investments as cited above), areas now considered to be DoD-specific, which are now the focus of DoD R&D investment, will likely move into the commercial mainstream as a result of the catalytic effects of that investment. Such areas include parallel computing, technology for high assurance, realtime systems technology, techniques for fault tolerance, lifecycle support environments and tools, reuse and repository technology, and component-oriented (megaprogramming) software development and management technology.

b. Logistics Infrastructure

As noted above, software support and logistics account for the vast bulk of DoD software costs. Improvements in software engineering processes and environments will enable architecture and component oriented systems management, with components more likely to be used in multiple systems, enabling shared support and logistics costs. In addition, software systems will be managed using fine-grained, configuration-controlled design records incorporating specifications, design decisions and rationale, system architecture and interfaces, code components, test cases, developer/maintainer documentation, user documentation, and other potential configuration items. These records will drastically reduce the need for reverse engineering in the support process, and enable more effective exploitation of automation to support system upgrade and testing.

A major rationale for adopting Ada over the proliferating DoD-specific programming languages is the reduction in support costs that is engendered through uniform support tools and policies. Ada, particularly as it and its tool base evolve, will provide more effective support for architecture conventionalization and use of reusable components, whose support costs can be shared.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Software and system engineering process and environments

(1) Objective

The objective is to permit process flexibility, to enhance management visibility and control over the process, and to create automation support for the full lifecycle process.

The software process consists of different kinds of activities, such as requirements engineering including prototyping, architectural design, detailed design, implementation, verification (establishing conformation of implementation with design specifications), validation (establishing conformance with actual requirements), and integration of software components. These activities are supported by management activities that enable teamwork, determine configurations, set standards, allocate resources (e.g., staff time, tool and computing support, access to testbeds), adjust design parameters, and provide other kinds of global control. The complexity and scale of a software process can be significantly reduced through the effective use of environment and tool support. Environments and tools are, in effect, the principal force multiplier in engineering organizations. Tool support exists for more than 50 distinct phases or elements of the software process. These tools are linked together by frameworks that support data interoperabilty, process representation and implementation, and uniform interaction with software engineers. DoD is catalyzing framework activity that will lead to accepted standards supporting multi-vendor tool interoperability, including interoperability of "conventional" software and "machine intelligence" software covered under Machine Intelligence and Robotics.

DoD has particularly demanding requirements concerning lifecycle, functional and performance requirements, supportability, integration, testing, and other areas. Because of the scale and complexity of the systems developed and managed, it also requires extensive tooling support.

(2) Development Milestones

- The milestones for this effort include:

  (a) By FY 1993, organizational process capability assessment in common use as a contractor selection criterion.

  (b) By FY 1995, DoD environment frameworks available, partially populated with commercial tools, and validated through development of software components in acquisition activities.

  (c) By FY 1995, process model notations supported by environment frameworks, with preliminary support for prototyping and iterative models.

  (d) By FY 1997, iterative process models for unprecedented systems supported by environment frameworks.

b. Real-time and fault-tolerant software

(1) Objectives

The objective is to facilitate the development of embedded systems of all kinds that operate in environments that require assurance that hard real-time deadlines will be met and that failures or faults in external sensors, controllers, or other processors can be tolerated with minimal impact on system performance and function.

(2) **Development Milestones**

- The major milestones for this effort include:

  (a) By FY 1993, scheduling algorithms and analysis techniques in common use for real-time uniprocessor systems.

  (b) By FY 1995, real-time operating system support for distributed and parallel systems emerging with commercial support.

  (c) By FY 1995, prototyping support for fault tolerant systems configurations to support reliability estimation.

  (d) By FY 1997, libraries of fault tolerant code for distributed systems.

c. **Reuse and re-engineering**

(1) **Objective**

The objective is to reduce costs and risks associated with software support and enhancement efforts through improved software development practices and tools, and through more effective process and tooling for support organizations. In addition, the objective is to facilitate creation and reuse of sharable software assets of all kinds, including architectures, interfaces, components, test cases, specification fragments, etc.

Successful reuse and re-engineering requires means to develop and codify domain-specific architectures and internal interfaces that can be utilized, at least in part, by multiple systems efforts, yielding both sharing of assets and ability to manage assets in a more component oriented manner.

(2) **Development Milestones**

- The milestones for this effort include:

  (a) By FY 1994, prototype national Ada repository available for experimental use.

  (b) By FY 1995, domain analysis yields usable domain-specific architectures for DoD-specific software domains such as avionics, guidance, C^3, and vehicle control.

  (c) By FY 1995, use of design record to capture data gathered during software developments and reverse engineering efforts used to support re-engineering and reuse.

  (d) By FY 1997, cost/benefit data collection to support reuse decisions in use.

d. **Software for Parallel and Distributed Heterogeneous Systems**

(1) **Objective**

The objective is to develop common systems software that can support heterogeneous distributed and parallel computing configurations with high performance, robustness, and high levels of application program support.

The systems software can include operating systems, data bases, file systems, and concurrency support tools. Advances in systems software are also critical to successful exploitation of advanced high performance computing systems, as covered under High Performance Computing.

(2) Development Milestones

- Milestones for this task include:

  (a) By FY 1993, widespread use of national file system supporting access control, robustness, and name management.

  (b) By FY 1994, robust operating system kernel support for heterogeneous distributed and parallel systems.

  (c) By FY 1995, robust, high performance distributed object manager system supporting software and CAD environment frameworks.

  (d) By FY 1997, application portability environment for high performance parallel and distributed systems.

e. High Assurance Software

(1) Objective

The objective is to create processes and tools that can support development of systems for which compelling evidence can be provided that certain specified system requirements are supported by the system. Typically, the requirements concern security or safety, but they may also involve deadline guarantees for real-time systems, assurance that a user display is accurate, or some other property.

The technology includes specification techniques for the critical requirements, methods and tools to analyze requirements specifications and implementations in order to provide assurance, and processes to certify that systems have certain kinds of properties, typically security properties.

(2) Development Milestones

- The milestones for this effort include:

  (a) By FY 1993, formal models for data confidentiality and preliminary formal models for data integrity.

  (b) By FY 1995, use of formal specification languages for selected components.

  (c) By FY 1996, iterative process models for high assurance software available for use.

  (d) By FY 1996, use of highly assured Ada components.

2. Technology Objectives

Technology Objectives — Software Engineering

Technical Area	By 1996	By 2001	By 2006
Software and system engineering process and environments	• Open architecture SEE framework with commercial acceptance and CASE interoperability • Iterative process models • Domain-specific prototyping capabilities for components • Robust design recovery tools	• Open architecture SEE with direct process support • Integrated project design information record • Process metrics supporting continuous risk, cost, schedule assessment • Initial process programmed software environment	• Hypermedia design information management across full life-cycle • Acquisition associate system supporting continuous process optimization • Machine intelligence assisted requirements elicitation • Pro-active knowledge based support in environments
Real-time and fault-tolerant software	• Operating systems interface standards supporting real-time • Real-time scheduling algorithms for mixed workload real-time tasks on uniprocessor	• Tool support for specification and formal analysis of small-scale real-time systems • Commercial operating systems kernels supporting real-time	• Synthesis of hard real-time schedulers for parallel processors • Automatic allocation of resources to processes for real-time systems • Hardware-independent models for distributed/ parallel real-time environments
Reuse and re-engineering	• Machine independent reuse of systems software components • Repository technology deployed, including national file system with access control	• Domain specific architectures and interfaces • Cost/benefit data collection for reuse and re-engineering • Distributed secure repository	• Precise codification and conformance testing for domain specifications • Reverse engineering tools supporting design recovery for fielded systems integrated into SEE frameworks
Software for parallel and distributed heterogeneous systems	• Heterogeneous distributed operating system supporting parallelism • Wide-area distributed file system with access control and limited replication	• Distributed reliable object management support with search and access control • Very high level languages for distributed object computation	• Adaptive, dynamic resource allocation for very large scale distributed computing • Databases with suport for advanced inference, full multi-media, and adaptive replication
High assurance software	• Confidentiality proofs for simple operating system kernels • High assurance system software products including operating system components and network gateways	• Iterative process models in use for development of high assurance software • Formal specification and analysis tools incorporated into software engineering environments • Environment support for high assurance Ada software components	• Integrity proofs • Software environment supporting design, development, and adaptation of highly assured software • High assurance distributed database management systems

3. Resources

Software has become a pivotal technology for a wide range of defense systems, and software capability continues to increase. Requirements placed on software elements of systems are increasing much more rapidly, particularly with the changes in the DoD environment towards more unpredictable threats, more rapidly changing interoperabilty requirements, more rapid mobilization and deployment, greater requirements for force multipliers, and the increasing need for high assurance as computer communications become ubiquitous. Because of the rapidly increasing needs, each of the Services, as well as DARPA, SDIO, and other agencies, sponsor significant research programs in software engineering. A summary of funding for software research is given in the following table.

A summary of total S&T funding for software engineering is given in the following table.

Funding — Software Engineering ($M)

FY87–91	FY92	FY93	FY94	FY95	FY96	FY97
384	149	148	153	155	156	157

4. Utilizing the Technology

Software technology is pervasive across major defense systems. Each of the Services and SDIO have systems that comprise more than one million lines of code (e.g., the Strategic Defense System, the Advanced Field Artillery Tactical Data System, the Standard Finance System Redesign, the AN/BSY-2 Submarine Combat Control System, and the Advanced Tactical Fighter). The software base relied upon for DoD information engineering can be developed and managed using largely the same technology as for weapons system software. Indeed, the commercial base upon which the information engineering efforts rely was largely catalyzed through DoD research investment.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

Although there are DoD-specific software technology requirements, such as for certain aspects of security and real-time systems, the DoD nearly always benefits by exploiting commercial capabilities. DoD benefits through what amounts to effectively shared product development and enhancement costs with all other customers, and, often, through the greater cost-effectiveness, robustness, and reliability that results from competitive pressures.

For this reason, DoD exploits commercial off-the-shelf (COTS) software where possible. In some domains, such as information systems, nearly all DoD needs can be met through commercial products with occasional customization required. This is because DoD requirements to support payroll and other routine operations are similar to requirements in other sectors. On the other hand, there are special requirements even in information systems that DoD addresses either through direct customization or, in the longer term, through the spin-on approach described earlier.

In cases where actual commercial modules cannot be exploited, commercial standards very often can. Commercial standards adopted by DoD include standards for programming languages, communications, data interchange, systems software interfaces, and so on. The DoD Computer-Assisted Acquisition and Logistics Support (CALS) program is involved in selecting and supporting interchange standards for use in the DoD acquisition process.

The commercial industrial base also provides a wide range of software tools, though effective multi-vendor integration is still lacking (though this is an area of DoD R&D focus). Tools available include Ada compilers, associated support tools, and many commercial "computer aided software engineering" (CASE) tools. Many of these tools were developed for use in the much larger business and manufacturing systems integration market; DoD, in its framework efforts, is seeking high levels of compatibility with these tools.

DoD also exploits scientific/engineering software packages that emerge from the commercial sector. Nonetheless, there are many DoD-specific requirements in all areas, and the extent to which DoD requirements will lead the market will likely increase. For this reason, DoD R&D investment continues to address both immediate DoD needs and longer term generic technology needs where DoD will likely have special requirements. As noted in earlier sections, this investment has yielded and continues to yield enormous impact in ensuring that DoD requirements can be effectively addressed.

2. Projected Industrial Capabilities

There are several likely areas of increased industrial capability, in many cases as a direct result of prior DoD investment.

One area is software environments and tools. Environment frameworks will emerge that will support multi-vendor tool integration, direct process support, and consistent user interface management. Because of the extent of industry consensus required, these results are principally the result of government investment. Leveraging the DoD investment in this area are other framework customers, including the VLSI and manufacturing CAD communities and the machine intelligence software community.

Advances in the areas of operating systems, generally as a result of DoD investment, will lead to advanced application portability profiles that will enable a higher degree of integration of diverse application software on advanced workstations. This will yield benefits for DoD information systems and office systems.

In some years, commercial capabilities may emerge to provide effective generic kernel support for real-time and fault tolerant systems.

The bottom line is that continued effective DoD R&D investment strategy will yield a continuous stream of commercial advances that will address a wide range of DoD needs. There will nonetheless remain a substantial body of unmet highly DoD-specific needs. These requirements, however, can often be addressed using hybrid systems approaches, involving use of domain-specific architectures populated by components, some of which are COTS and others of which are developed and managed by DoD and its contractors. With appropriate design documentation record support, management of these hybrid systems can exploit continued growth in capability of the commercial components, as spurred by the market, and growth in computational power of the underlying computing systems base.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

The National Science Foundation (NSF) sponsors basic research in software technology, with an emphasis on smaller scale projects, though there are several larger centers sponsored by NSF that engage in experimental research. Although moderate-scale prototype engineering activity is now more frequently undertaken, most NSF support is provided to individual researchers. NSF supports basic research in software engineering and technology, with an emphasis on quality, reliability, productivity, and exploitation of parallelism. NSF Advanced Scientific Computation centers provide researchers with access to high performance computing systems.

Many agencies have Ada-related activities, including FAA and NASA. NASA is already utilizing Ada on the Space Station Freedom Program and is sponsoring a major Ada-based software engineering environment. NASA sponsors a significant range of software efforts (e.g., at Goddard, Langley, and JPL) that bear on DoD goals such as realtime, fault tolerance, high assurance, and software lifecycle support.

NIST conducts research focused on high integrity software by developing technologies that address software assurance and quality. Research includes formal methods for specification and verification, and quality assurance techniques based on testing and statistical methods.

The Subcommittee on Investigations and Oversight of the House Committee on Science, Space, and Technology issued a report in August 1989, entitled, "Bugs in the Program: Problems in Federal Government Computer Software Development and Regulation" addressing software quality and assurance-related issues.

Software for high performance systems is one of the four principal elements of the Presidential High Performance Computing and Communications initiative announced in February 1991. Technical elements of this program are described under High Performance Computing.

2. R&D in the Private Sector

Computing technology accounts for a significant portion of the GNP, and there is considerable R&D underway in the private sector. Nonetheless, as indicated above, government-sponsored research efforts have a disproportionate effect on the marketplace, and considerably accelerate the process by which DoD technology needs are addressed. Government contractor IR&D provides another accelerator for DoD software technology.

Commercial product R&D has resulting in a vast array of software engineering tools and related management products, including not only compilers but also design and other software engineering tools. Most of the DoD information engineering needs are addressed directly as a result of commercial R&D, though there are cases where DoD R&D investment is required in order to ensure that special requirements are effectively addressed.

Several industrial consortia have been formed to address aspects of software technology, such as the Software Productivity Consortium (SPC) and the Microelectronics and Computer Technology Corporation (MCC). In addition, industry has affiliations with (but does not fund) the DoD-funded Software Engineering Institute (SEI), which is an FFRDC. The primary mission of the SEI is to support technology transition for software engineering capability into defense systems.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

The following technologies are indicative of the capability of a nation in software technology.

- Software development environments, including automation support for requirements engineering, cost analysis, rapid prototyping, and associated library and management support capabilities.
- Operating systems and applications to support real-time information management in large, distributed computer operations.
- Algorithms, languages, and software engineering methods and tools to take full advantage of the performance potential offered by advanced computer architectures.

The table on the following page provides a summary comparison of the United States and other nations for selected aspects of the technology.

Summary Comparison – Software Engineering

Selected Elements	USSR	NATO Allies	Japan	Others
Enhanced software development environments	□	□□□□ O	□□□ –	
Operating systems and applications software to support real-time information management in large, distributed systems	□	□□	□□	
Algorithms, languages, and tools for advanced parallel architectures	□□	□□	□□□	□□ [a]
Software process management	□□	□□	□□□□	
Overall Evaluation[b]	□	□□	□□	□□

[a] Many countries have ongoing theoretical work in algorithms. Individual breakthroughs are possible from any of these efforts, but cannot be predicted or planned.

[b] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□ broad technical achievement; allies capable of major contributions

□□□ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions

□□ generally lagging; allies may be capable of contributing in selected areas

□ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators – where significant or important capabilities exist (i.e., 3 or 4 blocks):

\+ Foreign capability increasing at a faster rate than the United States

O Foreign capability increasing at a similar rate to the United States

– Foreign capability increasing at a slower rate than the United States

The USSR has demonstrated strong theoretical capabilities in computer science. Soviet researchers have mastered numerous theoretical techniques for the automated production of software. Institutes and plants supporting military R&D and production are likely to be the first to assimilate these new techniques. The Soviet computer science community has also developed a strong capability to produce software for highly parallel computers. The application of software technology, however, continues to be an area of serious deficiency, much of it stemming from a shortage of computers, especially microcomputers and supercomputers, and from reliability problems, especially with peripherals. Soviet programmers lack adequate hands-on computer experience. Computer-to-computer networking is rare except in high-priority applications. The situation is exacerbated by the poor quality of public telecommunications and poor technical communications among S&T professionals.

There has, however, been a conspicuous trend in the Soviet military literature, beginning in the early 1960s, to stress cybernetics and operations research as elements in military decision making. The literature refers to the computer as a "comrade-in-arms," in addition to acknowledging its role as a consultant and information source. The issue of computer security has become as important to the Soviets as it has to the United States. It is highly unlikely, though, that Soviet computer security is any better than that of the United States.

The European and Japanese communities are developing partnerships among government, industry, and academia at a much faster pace than the United States. However, the research into software technology in the United States is, at this point, probably more advanced than in Japan and Europe, though this is not true in all specific technology areas.

There are two ongoing cooperative efforts with European countries to develop standard interfaces for Ada programming support environments.

The Japanese have made significant progress in developing process and management techniques to support reuse in specific applications areas (the Japanese "software factory"). Japanese efforts in compiler development for vector parallel computers are also very advanced.

NATO has adopted Ada as a standard programming language and individual NATO countries have either adopted or mandated the use of Ada in military systems. Software development has been an area of major emphasis in European research funding programs, and multinational ventures in Europe have the potential for achieving comparability with the United States by combining individual strengths. Large-scale European projects are sponsored by the European Strategic Program for Research in Information Technology (ESPRIT) and European Research Coordination Agency (EUREKA), using joint industrial and government funding. Planning documents indicate that approximately 20 percent of the approximately $1 billion total annual budget for these consortia is allocated to software, not including office systems and artificial intelligence. Explicit emphasis is given in ESPRIT to "pre-competitive collaborative" efforts leading to the development of common software interfaces (e.g., PCTE+) and portable tools. The EUREKA program, with a total cost of about $7 billion provided primarily by industry, promotes collaboration through coordination. Two of the key EUREKA programs are EUREKA Advanced Software Technology (EAST) and European Software Factory (ESF). A key new program is the European Software and Systems Initiative (ESSI). ESSI is aimed at increasing software productivity, and is funded at $600 million from 1990 to 1994. Additional emphasis on the use of formal methods to develop highly reliable software has led to a European lead in many specific technology areas. The UK Ministry of Defense has promulgated a draft standard for safety of critical systems involving the use of formal methods.

Outside of NATO and Japan, virtually all industrialized nations have some efforts relating to the development of specific algorithms. The nature of this research lends itself to individual breakthroughs in specific algorithms. These may contribute to significant advances beyond existing U.S. capabilities, but cannot be predicted.

2. Exchange Agreements

The NATO Defence Research Group (DRG) programs in operations research and long-term research for air defense provide a mechanism for exchanges of information on requirements for improved software technology. The Technology Cooperation Program (TTCP) sponsors a group on software engineering as well as a range of other applicable exchange activities, including computing technology, trusted computer systems, and machine and system architecture. The Services also have exchange activities, primarily with NATO nations. Ongoing Service exchange programs exist, for example, in software development methodologies, techniques and tools, distributed command and control, signal processing, flight control, cockpit systems for advanced fighters and helicopters, and computational fluid dynamics.

MOUs on Ada technology exist, for example, with France, Sweden, and Germany.

3. HIGH PERFORMANCE COMPUTING

3. HIGH PERFORMANCE COMPUTING

A. DESCRIPTION OF TECHNOLOGY

Rapid improvements in the performance and cost effectiveness of computer hardware, enabled by integrated microelectronics technologies, have spread computing into all areas of military and civilian life. Such rapid improvements in the speed of computing have come primarily from advances in the understanding of the physics and fabrication of electronic materials and devices. As the fundamental speed limits of materials properties are approached, further significant speedup is more likely to come from new architectural approaches. Average performance increases of 50 percent per year, sustained for the past 30 years, have produced computers capable of executing about 300 million operations per second as uniprocessor vector machines. These processors have been used in small scale shared memory multiprocessors such as the Cray Y–MP, which can sustain about 2 billion operations per second. Scalable parallel computer architectures will play a key role in maintaining this momentum. Advanced integrated microelectronics technologies and the corresponding reductions in cost per microelectronic device have made large-scale parallel systems feasible, opening a path to systems of even higher performance. Performance is expected to exceed one trillion operations per second by the mid 1990s as a result of the Presidential Initiative in High Performance Computing and Communications described in a supplement of the President's FY 1992 budget submission. Trillion operations per second computing systems will require billion bit per second networks to ensure a balanced high performance computing technology base. Defense is fully supporting this initiative in the DARPA HPC program because the multiple use high performance computing and communications technologies are critical to developing future Defense capabilities.

Technology Sets in High Performance Computing

- High performance computer systems
- Advanced software technology and algorithms
- High performance networking
- Basic research and human resources
- Defense specific technologies

These areas are consistent with in the Federal High Performance Computing and Communications Program,[1] which will be producing multiple use technologies, with the addition of defense specific technologies. The major technology areas listed above can be characterized as follows:

- *High performance computing systems* developments are in four main areas: research for future generations of computing systems, system design tools, advanced prototype systems, and evaluation of early systems. Systems capable of sustaining 100 gigaops for large problems will be available for deployment by late 1993 and the teraops systems will be available by 1996.

[1]The contents of this section are based upon the report "Grand Challenges: High Performance Computing and Communications" that was a supplement to the President's Fiscal Year 1992 Budget.

- *Advanced software technology and algorithms* covers scalable libraries for defense problem domains, programming, and analysis tools for scalable parallel and distributed heterogeneous systems in a workstation/server configuration that will be open to the integration of embedded system and accelerators.
- *High performance networking* technologies will be produced to satisfy the defense needs for gigabit networks. This networking technology will be capable of supporting a wide range of advanced network services, with bandwidth and traffic characteristics that are representative of the future networks.
- *Basic research and human resources* addresses long term national needs for more skilled personnel, enhancement of education and training, and materials and curriculum development in the high performance computing science and engineering areas. It is designed to encourage investigator initiated, long term research on experimental projects that will maintain the flow of innovative ideas and talented people into high performance computing areas. It will establish industry, university and government partnerships to improve the training and utilization of personnel and to expand the base of research and development personnel in high performance computing science, technology and applications.
- *Defense specific technologies* will focus on the special needs of defense for embedded systems such as high density packaging, special accelerators, realtime, fault–tolerant systems, and Defense applications to enable significant new capabilities.

B. PAYOFF

1. Impact on Future Weapon Systems

a. Weapon System Performance

Computer system technology is expected to continue to provide a critical edge in performance for all classes of weapons, command and control systems, and development of complex, distributed battle management systems such as smart weapons with integrated C3I systems platforms, or Strategic Defense systems. Weapon system accuracy and corresponding lethality, plus improved performance in naval, ground, and air vehicles, will be significantly enhanced through the exploitation of parallel computer architectures. High performance parallel computing will enhance DoD systems in both system design and their implementation to achieve new defense capabilities. These improvements will occur through anticipated advancements in materials science, computational fluid dynamics, semiconductor design, and machine vision that are enabled by high performance parallel computers. For example, simulation, as in Simnet, strategic defense, or theater battlefield war gaming, will exploit a variety of scalable, parallel computer architectures.

In the new defense systems, military platforms will be able to carry high–performance parallel processors and be able to provide new defense capabilities (onboard signal processing vastly superior to current airborne systems is conceivable). Similarly, the notions "smart hulls" for submarines and "smart skins" for aircraft are dependent on high–performance, parallel computing systems. High–performance, embedded systems are crucial for automatic target recognition capability by smart weapons. One–thousand–fold performance increases over present systems would find applications in large–array acoustic

ASW systems. Highly reliable embedded computers and space-qualified embedded processors are being developed for several DoD systems. High performance computing can also be used to enable predictive modeling of atmospheric and oceanographic events, which can have a significant effect on military operations and weapons systems. In benign environments commercial parallel processors are applicable.

b. Weapon System Logistics

Although scalable parallel systems may have thousands of processors, they represent no more system complexity than exists in today's supercomputers. Advances in microelectronic technology have enabled these parallel systems to be based on units of replication of both software and hardware. In other words, the embedded systems of the future could be based on the same components as the largest HPC systems, thus forming a single family of computing systems based on the same architectural concepts and manufacturing technology. Consequently, logistics, including software maintenance, will be more efficient. Maintenance will be simpler since the focus will be on units of replication and individual processor failures on the new scalable systems need not be fatal. Training will be simpler since programming styles and models of computation will be uniform for a wide range of systems— small embedded systems to the largest scale HPC systems. A single modern microprocessor can out-perform most large embedded uniprocessors deployed in current defense systems. Scalable parallel systems will create new opportunities for more efficient logistics.

High performance computing provides capabilities for self diagnosis, repair and recovery. The re-routing of communications networks is now exploited commercially and will be applied to high capacity networks.

Large scale problems created by logistics of rapid overseas deployment can be handled by high performance computing based planning and control functions.

2. Potential Benefits to Industrial Base

a. Manufacturing Infrastructure

High performance computing is a pervasive and powerful technology for industrial design and manufacturing, scientific research, communications, and information management. A strong U.S. high performance computing industry contributes to our leadership in critical national security areas and competitiveness in broad sectors of the civilian economy. High performance parallel computing will significantly affect the industrial base because of the increasing use of computation to augment experimental and theoretical approaches to science and engineering. Parallel computer designs may be scaled over a wide performance range (scale factor of 1,000 or more from the smallest system to the largest). These systems are also more effective in terms of cost, performance, volume, and power than conventional high performance computers. The first generation of parallel computer systems has recently emerged in commercial products in large part as a result of DARPA investments. The second generation is currently under development, with systems expected to emerge in 1992. High performance computing realized as scalable parallel and distributed systems with associated networking technology, systems software, software development environment, and trained personnel represents a fundamental enabling technology for the United States in the new information technology age.

Markets and applications will drive industrial investments in parallel computer architecture technology. By 1993, the top five markets will be government, aerospace, petroproducts, electronics, and research. Applications of this technology include computer-aided engineering and simulation and modeling. U.S. airframe manufacturers are already using massively parallel processing to replace expensive wind tunnel and radar range tests in aircraft design and are developing engineering simulation software that can also be run on training simulations.

b. Logistics Infrastructure

New equipment, skills, and training will be required at DoD depot environments in order to support and maintain systems incorporating parallel computer architectures. New computer languages and algorithms, which began to emerge in the 1980s, will need to be learned. New test equipment and diagnostic approaches will need to be developed in conjunction with these new capabilities. Essential capabilities to support systems with embedded parallel computer architectures may present challenges equal to that of the new architecture development, and this critical technology strategy must address both of these development aspects in parallel. The Defense logistics infrastructure will benefit from hardware and software technologies that are compatible with the commercial technology base.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

The DoD High Performance Computing (HPC) program under DARPA leadership is an integral part of the Federal Government High Performance Computing and Communications Program which also includes NSF, NASA, and DoE efforts. As the DoD element of the HPCC program builds up, the ongoing DARPA Strategic Computing Program will focus on the more defense-specific needs such as embedded systems, accelerators of specific problem domains, and critical problems related to defense. DoD is evaluating the use of such computing capability in a variety of critical military applications. For undersea surveillance, generalized modules have already been developed; new spatial processing algorithms will be available by FY 1992, and an array element location capability will be available by FY 1992 and demonstrated by FY 1993. For acoustic FDS visualization, DoD has implemented highly parallel meshes for mapping and will demonstrate a human-engineered display workbench with integrated FDS HDTV/net. C3I application efforts have formulated optimal selection theory (DINS). A CINCPACFLT training demonstration is planned for FY 1992 which includes implementation of distributed data bases on parallel computers. Development efforts are also focused on signal processing for IR/FPA sensors. A video display will be demonstrated by FY 1992. An alternative sensor processor will be prototyped and evaluated by FY 1993 and an optimized parallel computing design and algorithm approach demonstrated in FY 1994. The major objective of DoD's development program in parallel computer architectures and high performance computing is to develop the component, packaging, and design technologies for high performance computing systems. A variety of advanced application domains are being explored as DARPA Strategic Computing applications. Embeddable systems will be developed for defense specific uses.

a. High Performance Computing Systems (HPCS)

(1) Objectives

Development of parallel computer systems capable of sustaining trillions of operations per second on large problems including the associated networking for distributed systems and system software for use in a modern software engineering environment.

(2) Development Milestones

The High Performance Computing Systems technology area produces balanced scalable parallel computing systems through the development of prototype systems. These systems are developed with progressively larger scale, more advanced components and packaging, and more advanced designs. The program is structured to focus on major risk areas and to minimize the number of risk areas addressed in any given project. The projects are also structured by maturity. Larger projects which may provide the basis for the development of commercial products are performed on a cost-shared basis with industry. Critical underlying technologies are developed in prototype form with associated design tools, providing experimental evaluation of alternatives for potential use as they mature in prototype systems. Fundamental alternatives for critical technologies not otherwise available are developed as required to ensure that the system performance goals can be achieved. Systems are evaluated throughout the development process, and experimental experience is fed back into the design process for successive generations.

High Performance Computing Systems will be produced in four main subareas: Research for Future Generations of Computing Systems, System Design Tools, Advanced Prototype Systems, and Evaluation of Early Systems. Systems capable of sustaining 100 gigaops for large problems will be available for deployment by late 1993 and the teraops systems will be available by 1996.

b. Advanced Software Technology and Algorithms (ASTA)

(1) Objectives

Development of generic software technology and new algorithms to exploit the performance potential of scalable parallel and distributed heterogeneous high performance computing systems with advanced workstations in a high performance networking environment.

(2) Development Milestones

Scalable parallel and distributed systems provide new opportunities and challenges for software and algorithms. While much of what has been learned about more conventional computing systems can be used as a foundation, it needs to be extended to support the new large scale systems that will be produced in this program. A typical user environment will be an advanced workstation with high resolution color displays connected to a high performance network and local high performance computing resources. Access to additional high performance computing systems is available through regional and national networks. Realizing the full potential of teraops computing and gigabits networking will require advanced software technology and algorithms.

In Advanced Software Technology and Algorithms, DoD projects will produce scalable libraries for Defense problem domains and programming and analysis tools for scalable parallel and distributed heterogeneous systems in a workstation/server configuration that will be open to the integration of embedded systems and accelerators.

c. High Performance Networking

(1) Objectives

Development of a gigabit per second communication network to provide distributed computing capability among researchers and research institutions which may also be used in the development of large-scale distributed systems.

(2) Development Milestones

A new generation of high performance networking technology is required to support the sustained growth of the high performance computing infrastructure. Just as an individual computing system needs to be balanced, the associated networking technology needs to have sufficient capacity and provide the kind of services required by the user community. The new network technologies will enable resource sharing and cooperative research, development, and transition described in the program.

Networking at gigabit/sec data rates will require fundamentally new approaches than today's megabit/sec data rates due to such factors as the large amounts of data in the channel, the relative delay in acknowledging receipts, and error recovery. The network protocols in use with today's megabit channels have evolved from the older 56 kilobit channels and are not expected to extend much further. In addition, a much wider range of services is required over the dimensions of burst rates, sustained data rates, and error recovery. The types of service required include: traditional character at a time for simple remote access, file transfer over a wide range of sizes, wide area file systems as an extension of local network file systems, remote window systems with graphics, video conference, and large-scale distributed systems.

For the National Research and Education Network (NREN) component, high performance networking technologies will be produced to satisfy the gigabit technology needs of the NREN and to provide a dual use technology base for DoD. This networking technology includes development of new protocols and switch and transmission technologies, and it will be capable of supporting a wide range of advanced network services.

d. Basic Research and Human Resources (BRHR)

(1) Objective

Basic Research and Human Resources addresses long term national needs for more skilled personnel, enhancement of education and training, and materials and curriculum development in the high performance computing science and engineering areas. It is designed to encourage investigator initiated, long term research on experimental projects that will maintain the flow of innovative ideas and talented people into high performance computing areas. It will establish industry, university and government partnerships to improve the training and utilization of personnel and to expand the base of research and development personnel in high performance computing science, technology and applications.

(2) Development Milestones

The Basic Research and Human Resources component will focus on fundamental scientific issues in the order to:

- Improve the flow of human resources into high performance computing
- Improve the university infrastructure in high performannce computing
- Facilitate multidisciplinary academic research on high performance computing and communications.

e. Defense Specific Technologies

(1) Objective

Develop the additional technologies needed to enable the use of parallel computer architectures and associated networking and system software technologies in defense systems.

(2) Development Milestones

The Defense Specific Technologies component will focus on transitions of high performance computing technology from the multi-use technology base into specific defense requirements such as embedded computing, application specific accelerators, distributed systems, and heterogeneous systems that are fault tolerant and survivable.

2. Technology Objectives

Technology Objectives — High Performance Computing

Technical Area	By 1996	By 2001	BY 2006
High performance computing systems	• Teraops systems (Tera = 10^{12}) • Multi chip modules package • Heterogenous systems • Multi teraop designs	• 100 Teraops systems • Optical interconnect • Petaops designs	• 10 Petaops systems (Peta = 10^{15})
Advanced software technology and algorithms	• Scalable libraries • Design tools • Support for heterogeneous computing	• Deployed scalable programming environments with integrated software engineering	
High performance networking	• Gigabit networks available for deployment • Multi-gigabit designs	• 100 Gigabit available for deployment • Terabit designs with all optical data paths	• Terabit deployable
Defense specific technologies	• Embedded systems with Teraop components	• Embedded systems with 100 Teraop components	• Embedded systems with PETAOPS components

3. Resources

Total S&T funding in this critical technology is shown below.[2]

Funding — High Performance Computing ($M)

FY87–91	FY92	FY93	FY94	FY95	FY96	FY97
414	172	219	273	301	349	350

4. Utilizing the Technology

DoD is a major current and future user of high performance parallel computing technology. The DoD laboratories exploit parallel machines for a wide variety of numerical and symbolic computations in ASW, strategic defense, quantum physics, fluid dynamics, and natural language understanding. Activity is underway to determine the most effective processors for ASW signal processing. The AN/BSY-2 submarine combat control system currently under development uses a loosely coupled parallel processor design. DoD is also using parallel computing to support development of the next generation tactical fighter aircraft. In addition, parallel processors have been demonstrated or will be exploited for standoff minefield detection, multi-sensor target acquisition demonstration, distributed communications systems, and distributed C2-force level control.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

First generation scalable parallel systems are now commercially available from US vendors. Makers of parallel computing equipment fall into two principal categories: supercomputer vendors (there are 6 domestic firms) and minisupercomputer vendors (approximately 23). Since 1976, the supercomputer market has been one of the most stable high technology growth markets, with growth estimated at 7 percent annually from 1989 to 1992, while the minisupercomputer market will grow 28 percent annually during the same period. As a result of DARPA investments in the 1980s, a new industrial base in development and use of scalable parallel architectures has begun to emerge. Although the market is still small, it is considered a critical enabler of a broad range of critical defense capabilities. DoD-sponsored investments in manufacturing technology are focused on microelectronic needs (Gallium Arsenide. VHSIC, wafer preparation and packaging, integrated circuit manufacturing).

2. Projected Industrial Capabilities

Specific plans related to manufacturing technology will be driven by growing market pull from large commercial and scientific markets that were once the exclusive domain of the mainframe and are moving rapidly to scalable, parallel processing. Most U.S.-based supercomputers and nearly all minisupercomputers have introduced parallel architectural concepts into their systems. It is estimated that nearly half of the systems shipped in 1991 will contain parallel architectural concepts and some of these will be scalable parallel systems.

[2]The funding levels shown include primarily 6.2 funding consistent with the definitions found in the Federal High Performance Computing and Communications Program published by the OSTP in 1989.

Because of increased emphasis on advanced computing by Japanese computer manufacturers (with strong government backing), a highly competitive environment will be evident.

Because of the prevalence of high performance computing across so many Defense and non-Defense technologies, a proposed 5-year, $2 billion high performance computing and communications plan that would support the development of advanced systems was given the backing of the Office of Science and Technology Policy (OSTP) and DARPA and is included in the President's FY 1992 Budget. This Presidential initiative, "Grand Challenges: High Performance Computing and Communications", focuses on accelerating significantly the commercial availability and utilization of new generations of high performance computers and communications networks. The Program addresses both government and private sector producers in defense and commercial applications.

Special manufacturing needs for development of parallel computer architectures are closely aligned to the semiconductor and microelectronic market in the United States. The technology base for networking is similar to computing with additional requirements for high performance switching and high data rate long distance communication channels. Development of these advanced systems requires random access memory chips to utilize this high-speed computing technology. Other related industries and technologies include software, distributed data bases, parallel and distributed computation, heterogeneous systems, computer-human interface, and networking and communication.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

The DoE has active programs in a number of parallel computer architecture areas:

- Robust computing infrastructures
- Methods development and implementation for major applications
- A small number of experimental supercomputing centers established through the national laboratories
- Use of government research centers in educational initiatives.

DoE in particular is fostering education through a series of post-doctoral and predoctoral fellowships, through its efforts to provide a center for parallel computing that would be open to researchers and students from other institutions (a DARPA/INTEL collaboration in DARPA's Touchstone project, networking collaborations with AT&T Bell Labs, and architecture research collaborations with industrial firms). DoD research at universities focuses on parallel algorithms, software development environment and techniques for parallel machines, and instrumentation and monitoring techniques for parallel architectures. University research is also concentrating on the development of parallel programming environments to permit effective utilization of parallel computer architectures, especially for scientific computing applications. A major research program to develop an integrated programming environment for shared memory architectures is underway at the University of Illinois.

NASA is actively supporting the development and utilization of parallel computer architectures. Driven by agency mission requirements, NASA developed an early large scale parallel computer, the Massively Parallel Processor (MPP). The technology developed and the lessons learned have transitioned to several of the MPP's commercial successors.

NASA is currently integrating a number of parallel processors into its institutional computer centers such as the Numerical Aerodynamic Simulation Facility at the Ames

Research Center. Processors are both large grain and fine grain parallel. NASA invests even more of its annual budget in the development of algorithms, applications, and system software for parallel processing in its field centers, research institutes, and university-based centers of excellence. The list of the facilities developing or utilizing parallel processors under NASA funds includes (but is not limited to): Ames, Lewis, and Langley Research Centers, Goddard Space Flight Center, Jet Propulsion Laboratory, Stanford University, and the University of Illinois.

The objective of the NIST *Performance Measures for Advanced Computers* program is to devise ways of measuring the performance characteristics of high performance multi-processor machines, particularly multiple-instruction machines based on shared and distributed memory architectures, without significantly degrading the performance. Studies to date demonstrate that the performance of a system may be characterized by a few system state parameters, thus indicating that compact, predictive models of performance are possible. NIST's responsibilities in the Federal High Performance Computing Program are to promote "open" software systems, and support a classification system for indexing and distributing scientific software so that industry and the research community can effectively exploit the power of future generations of high performance computers.

NSF support for research on parallel computer architecture is provided primarily through activities in computer and computation theory, computer and microelectronic systems architecture, software systems and engineering, and experimental systems. In addition, NSF funds the Center for Research on Parallel Computation. Researchers are provided access to massively parallel computers at four NSF supercomputer centers.

The Army has designated the University of Minnesota as the location of an Army High Performance Computing Research Center for Army applications. This center is a five-year effort involving acquisition and networking of high-performance computing architectures in a heterogeneous environment, basic interdisciplinary research in the optimal exploitation of problem structure and parallel architectures in the solution of problems in science and engineering, and the transfer of expertise in parallel processing from the center to DoD scientists in an infrastructure support program of internships, on-site tutorials, consulting, technical reports, and hands-on parallel computing experience. Furthermore, the development of parallel software systems required to support the center will directly affect productivity in parallel software development, which lags far behind developments in parallel processing hardware.

2. R&D in the Private Sector

Defense investment in high-performance parallel computing has spawned a number of industrial product lines, mostly oriented toward commercial applications. Industry generally considers exploitation of massive parallelism into the teraops range as too risky for development. Instead U.S. industry has pursued incremental improvements in older approaches to computing. University research is concentrating on the development of parallel programming environments to permit effective utilization of parallel computer architectures for scientific computing applications.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- **Design of scalable, parallel, distributed, heterogeneous computing with capability of 10^{11} to 10^{12} floating point operations/sec.**

- Improved packaging (including interconnect and thermal management) for massively parallel hardware
- Development of software and software development tools to exploit massive parallelism
- Development of trusted operating systems for distributed, parallel computing.

The table on the following page provides a summary comparison of the US and other nations for selected key aspects of the technology. The United States has a significant worldwide lead in serial production and practical application of parallel processing hardware. This lead developed from and continues to be supported by the US capability in microprocessors and a broad experience base in advanced computing hardware design and packaging.

There is no evidence that the USSR has achieved significant success in high-performance computing, however, technology transfer from former satellite countries is possible. The Soviets have historically followed the United States by 10 or more years in computer systems, and there is no indication this will change. The Soviets are, and will continue to be, severely hampered by lack of capability for quantity production of high-speed digital components and assemblies (see Semiconductor Materials and Microelectronic Circuits). Thus, their strengths are likely to remain largely in theory, research, and prototyping. While the Soviets have a significant research effort in parallel computing, they are many years from being able to provide their scientists and engineers with the levels of technology available to their Western counterparts. The increased availability of microprocessors enables the development of early forms of scalable parallel systems.

The United States, Europe, and Canada are pursuing parallel computing through increasing integration of processors. Japanese efforts emphasize peak vector processor performance. As a consequence, Japan has not produced massively parallel machines on par with the United States/Europe and Canada. However, their multi-processor computers have a much higher theoretical peak performance (TPP) than do their US/European/Canadian counterparts. U.S. technology continues to be dependent on Japanese memory chips and some high performance component technologies. Advanced U.S. scalable parallel computing systems have all of the processing components designed and produced by U.S. sources. Cooperative opportunities will exist with NATO countries, especially with the UK, the Netherlands, the FRG, and France.

Japan, the UK, the Netherlands, and Germany all have credible efforts in parallel computing. The Japanese have developed high peak performance production models of small parallel processing vector computer systems. NEC's SX-X/SX-3/3/44 series of computers was released in 1989 and has four processors capable of a TPP of 22 GFLOPS. The 16 processor Cray-3 has yet to be released (probably 1991), and is expected to be capable of 16 GFLOPS. However, the Japanese are several years behind the United States in highly parallel systems and associated software. As the commercial market becomes more significant, they can be expected to try to close the gap. The U.S. systems are generally able to sustain higher performance for important applications than Japanese systems.

Japanese R&D in parallel computing is beginning to show results. The Industrial Technology Agency's Electro-technology Laboratory has recently announced the development of a 128-processor configuration data flow system, the Sigma-1, a hardware prototype based on an earlier MIT dataflow design. The Japanese have developed only minimal demonstration software for this systems. The stated maximum processing speed is 640 million floating point operations per second (MFLOPS), placing the system in the supercomputer category. The Japanese have no work under way equivalent to the breadth and depth of U.S. projects or the UK transputer project described below.

Summary Comparison — High Performance Computing

Selected Elements	USSR	NATO Allies	Japan	Others
Design of massively parallel, distributed computing with 10^{11} - 10^{12} FLOP capabilities	□	□□	□□	
Improved packaging (including interconnect and thermal management) and massively parallel hardware	□	□□	□□□ ○	□□ Switzerland
Development of software and development tools to exploit massive parallelism	□	□□□ ○	□□	□□ Israel, Hungary
Development of trusted operating system for distributed, parallel computing	□	□□	□□	
Overall[a]	□	□□	□□	□□ Switzerland Israel, Hungary

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□	broad technical achievement; allies capable of major contributions
□□□	moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
□□	generally lagging; allies may be capable of contributing in selected areas
□	lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

+	Foreign capability increasing at a faster rate than the United States
○	Foreign capability increasing at a similar rate to the United States
—	Foreign capability increasing at a slower rate than the United States

The UK has a significant parallel processing software research effort and infrastructure in its universities, industry, and government establishments. Notable among these is the Alvey Program for Advanced Information Technology. The European Strategic Program for Research in Information Technology (ESPRIT) is also pursuing related software engineering initiatives. Specific areas of research include techniques for dynamic control of array topology and diagnosis and control of load balance in massively parallel processors. The Edinburgh concurrent supercomputer is presently using an electronically reconfigurable 200-processor array of Inmos transputers (3 MFLOPS per processor board) for a wide range of research and modeling applications. The ESPRIT project also uses the Inmos transputer and supports research in many areas. Applications include development of high-level programming languages and techniques for image processing and synthesis, scientific computation (including computational fluid dynamics), logic simulation, and artificial neural nets.

The UK was a primary contributor to the development of the OCCAM-I, -II programming languages, the first general computer language written specifically for parallel computers. Inmos, Limited (Bristol, England) developed and now produces a line of VLSI chips specifically designed to implement the OCCAM language. These transputers are the building blocks of a research program being pursued by the Royal Signals and Radar Establishment with support from Thorn EMI, Ltd., Inmos, and Southampton University to develop a real-time reconfigurable supercomputer.

Many other countries are involved with parallel computer architecture research based on the Inmos transputer, such as the Soviet Union, Germany, Hungary, Czechoslovakia, and Denmark. Hungary is working on a distributed version of PROLOG for transputers called CS-PROLOG and Germany is researching the use of transputers in space technology to process the enormous amounts of data collected on board spacecraft

Recently the Netherlands has become much more active in the field, especially in the areas of algorithms and the application of parallel architectures to artificial intelligence.

2. Exchange Agreements

Mechanisms for international cooperation in military applications of parallel computing are still developing in this relatively new field. The NATO Defense Research Group (DRG) programs in operations research and in long-term research for air defense provide a mechanism for exchanges of information to help understand and define essential requirements for future applications of parallel computing. The Technology Cooperation Program (TTCP) provides a direct vehicle under its program for machine and system architecture and for a range of applicable exchange activities under computing technology, software engineering, and trusted computer systems. These programs, together with technology exchanges in basic electronics, should also contribute to overcoming packaging and thermal management problems in assemblies with the extremely high component densities typical of massively parallel machines.

The Services also have exchanges, primarily with NATO and a few other friendly nations. Ongoing Service exchange programs in distributed command and control, signal processing, flight control, cockpit systems for advanced fighters and helicopters, and computational fluid dynamics support parallel computer architecture technology. DARPA has held an exploratory workshop with ESPRIT on a variety of topics including High Performance Computing.

4. MACHINE INTELLIGENCE AND ROBOTICS

4. MACHINE INTELLIGENCE AND ROBOTICS

A. DESCRIPTION OF TECHNOLOGY

Machine intelligence is the behavior exhibited by computer/robotic systems which, when exhibited by humans, is recognized as intelligent. These behaviors include knowledge, understanding, perception, cognition, reasoning, induction, inference, planning, reaction, learning, and problem solving.

Machine Intelligence and Robotics are related technologies with rapidly growing applications in modern, high performance complex weapons, command and control, and manufacturing systems. While few complex weapons can be described as robots, many involve robotic technology. Similarly, Command and Control (C^2) systems are emerging that permit field commanders to specify guidance, which is subsequently followed tirelessly through intelligent computational means. These weapons and C^2 systems are tightly coupled man–machine systems, carefully designed to make effective use of the unique capabilities of both man and machine.

The design of intelligent C^2 systems, intelligent machines, and robots requires combining event and/or object detection, situation assessment, and response planning with suitable machine controllers, machine learning, and man–machine interfaces. Therefore, this critical technology utilizes the results from many other technologies, coupled with complex system integration technologies. Intelligent machines will increasingly depend on advances in parallel computer architectures (for rapid control), software producibility (to handle the complexity of sensing and control), sensors (to provide inputs for intelligent action), data fusion (to combine the signals from many sensors), and composite materials (to facilitate light weight).

First–generation components of machine intelligence technology have proven their commercial worth in moderately complex applications. Expert systems, for example, provide advice and problem solving skills in specialized, well–constrained knowledge areas and are routinely used in medicine, electronic trouble shooting, product evaluation, financial analysis, and mechanical assembly planning. Speech recognition systems are being used for parcel routing, inventory taking, quality control inspection, air traffic control training, and dictation.

Technology Sets in Machine Intelligence and Robotics

- Image understanding
- Autonomous planning
- Navigation
- Speech and text processing
- Machine learning
- Knowledge representation and acquisition
- Adaptive manipulation and control

Critical technology sets include image understanding, autonomous planning, knowledge representation and reasoning, navigation, speech and text processing, adaptive manipulation and control, and machine learning. The major areas of research in machine intelligence and robotics represent technical challenges which, when met, will significantly contribute to weapon system performance, C^2 system robustness, and training efficiency.

Image understanding encompasses the sensors, hardware, and software components that automatically identify objects, from threat vehicles and aircraft, construct representations of terrain, buildings, roads, rivers and forests, or are used in diverse manufacturing applications to enhance quality and control through automated visual inspection systems and visual based planning systems. Autonomous planning is the software that permits machines to perform complex actions under broad human guidance, and to respond to unanticipated events under conditions of uncertainty. Navigation is the technology that permits air, ground, and underwater vehicles to autonomously move from one location to another with precision and robustness.

Speech and text processing systems will allow people to talk naturally to machines and to select, interpret, and translate a wide variety of text; both depend on natural language understanding. Knowledge representation and acquisition are basic intelligence techniques which provides methods for acquiring knowledge, rules, procedures, and plans that are utilized by autonomous planning, and navigation systems. Machine learning contributes the capability for computer programs to infer strategies of relevant control, manipulation, or understanding previously unexperienced situations, using knowledge that is acquired over the life of the program. Adaptive manipulation and control enables mechanical devices to quickly accurately, robustly, and safely interoperate in combined human/machine environments.

Robotics technology also involves controlling complex mechanical devices under the direction of computer software in response to either fixed a-priori assumptions, or dynamically changing requirements. Robotics mechanisms find a broad spectrum of applications in helicopters, missiles, ground vehicles, weapon systems, and manufacturing installations. Developing lightweight, high load bearing, precision articulated mechanical devices is a critical engineering challenge facing robotics technology. Requirements for these devices are ubiquitous in DoD applications and the defense industrial base, robotics systems are of particular interest in the welding of tank suspension systems, assembly of electrical equipment, and the fabrication of complex composite shapes and structures such as those found in the B-2 bomber. Through the integration of the technical components of this critical technology, the performance characteristics of unmanned air, ground, and underwater vehicles are enabled.

B. PAYOFF

1. Impact on Future Weapons Systems

a. Weapon System Performance

The battlefield of the future will be fast paced. Sensors and weapons will identify targets on a real-time basis. Intelligent machines will fuse, process, and analyze data and present usable results almost instantaneously. Development of algorithms and associated software to make such systems possible is a major challenge.

Enhanced speech systems will permit rapid, hands-free weapons control, data retrieval, and reporting in tactical environments; computer-aided maintenance in depots and in the field; plus simulated partners in training exercises. Enhanced text processing systems will enable automatic scanning and routing of large volumes of messages to reduce DoD manpower costs and to increase DoD ability to respond to crises.

Efforts also are underway to develop complex decision-making aids — a battlefield management system (BMS). By processing huge amounts of information, machine intelligence can provide much more efficient tools for effective military intelligence, data analysis, battle management assessment, timely decision making, rapid replanning, and survivability through distribution of tasking, machines, and data repositories. Thus, machine intelligence and robotics applications will reduce the need for manpower while improving human response times. Additional advantages will result from the use of autonomous robotic ground vehicles and unmanned aerial vehicles. Removing crews from hazardous environments and exposed platforms also will improve survivability.

With the introduction of composite materials into the design of robotic manipulator arms, the structural weight of the manipulator and the power requirements to operate the arm at high speed will be significantly reduced. These robotic devices (with lighter components) will accomplish missions such as weapon loading, minefield breaching, materials handling, refueling, and assembly more rapidly and with less power consumption. Understanding the dynamic response characteristics of robotic systems with components fabricated from high-strength composite materials will lead to the development of control procedures that will ensure the precise positioning of end effectors in compliant robotic devices.

In military systems of the future, machine intelligence and robotics technologies will comprise highly integrated subsystems that can sense the outside world from several different perspectives (sensor fusion) and respond through processing of behavioral knowledge and control actuators to perform specific purposes. These intelligent and, where necessary, hardened machines of the future will provide an efficient means to supplement, augment, and support human capabilities when exposed to hazardous conditions.

When combined with other critical technologies (such as microelectronics fabrication technology, and parallel computing technology), machine intelligence will improve automatic target recognition capabilities, allow truly effective critical and prognostic systems, create tactical decision aids, and produce advanced robotic systems. The integration of these technologies will have a significant effect in improving human understanding and contribute to new applications of speech recognition.

b. Logistics Infrastructure

The dynamics and complexity of logistics planning requires decision support tools that do more than provide data base access or spreadsheet solutions. This is a significant challenge in light of the acknowledged over-commitment of inventories and transportation capabilities. Tradeoffs (relaxing constraints) to resolve logistics shortfalls have "penalties" in the sense that they may create shortfalls in other capabilities. Assessing the impact of tradeoffs across time and space is virtually impossible when the analysis is conducted manually. The application of machine intelligence will enable logisticians to move from manual planning to a computer-aided decision support environment including digitized terrain displays, graphical interfaces, and knowledge-based planning techniques. Knowledge-based planning is a powerful alternative to so-called "conventional" approaches to solving complex planning, scheduling, and logistics problems.

Planning efficiencies must be coupled with material handling and transportation efficiencies. The use of robotics and machine intelligence will be essential to the realization of acceptable risks associated with any realistic, system-wide material management economies. Robotics and machine intelligence will provide the means to maintain the uninterrupted flow of combat consumables in the presence of chemical and biological agents and other hazardous environmental extremes.

Automated learning technologies for expert systems are in their infancy. Knowledge based, expert systems, and AI approaches have great potential for maintenance and support functions, but must be planned to evolve as the target systems and/or knowledge bases change. Testing, quality control, and verification and validation (V&V) capabilities for these systems are limited. For example, with rule-based systems the only conclusive technique currently available for V&V is exhaustive testing, which is impractical for any application with a large number of rules. Technologies and capabilities that might provide structure and guidance for identifying knowledge base and metaknowledge update needs have not been developed. Further, software maintenance and sustaining engineering techniques needed to define and implement enhancements are not well developed.

Technology advances necessary to identify faults and reasoning errors in intelligent machines are essential for effective applications over extended life cycles. Therefore, the advanced capabilities to locate, correct, and validate updates to smart systems must be developed concurrently with the basic technology.

Intelligent self-diagnostic on-line and off-line systems will improve readiness and reduce maintenance and logistics costs. For example, recent studies have shown that expert system-based diagnostics can reduce maintenance man hours by as much as 30 percent, component false removals by 50 percent, and maintenance test flight requirements by 50 percent. Intelligent diagnostic systems with adaptive built-in-test (BIT) are needed that will learn and adapt correction procedures based on use experience.

This technology may be used to dramatically improve diagnostics and maintenance training through intelligent maintenance aids. It will also be used to provide diagnostics instruction geared specifically to the skill level of the individual. Such improvements will include supplementing work force as well as reducing personnel risks. For example, it can be applied to robotics for handling of heavy loads or hazardous materials.

As the technology within new systems evolves, greater levels of functional integration will occur. These future systems will incorporate new expert system capabilities such as graceful degradation; automated electronic module sharing; selfchecking hardware and software; and electronic technical information capture, distribution, and display. Adaptive, self-diagnosing, flight control systems currently under development exemplify future applications and opportunities.

2. Potential Benefits to Industrial Base

a. Manufacturing Infrastructure

The biggest users of robots in the U.S. commercial sector are the auto industry and the electronics industry. Robots perform highly repetitive tasks (such as spot welding in the auto industry and automatic pin insertion in the electronics industry). Industrial robotic systems also manufacture DoD materiel.

There are widespread industrial applications for machine intelligence and robotics, ranging from the handling of hazardous materials to automation in manufacturing. Expert systems are beginning to play a significant role in the design of complex objects to be fabricated, both in verifying designs suggested by human engineers and in suggesting novel designs autonomously. Robots, already used in simple parts assembly, will become increasingly adaptive to new tasks. Machine intelligence approaches to problem solving also will yield software for the automated planning and control of factory processes, from materials acquisition to product distribution. Robotic skills in dextrous manipulation will be supplemented by the rapid recognition examination of objects through image understanding and tactical information processing.

Applications of robotics and intelligent machines in manufacturing environments will result in flexible manufacturing capabilities with shortened set-up and production lead times, greater industrial base surge capabilities/capacity, enhanced quality, and reduced acquisition costs. Intelligent self-diagnostic on-line and off-line systems will improve readiness and reduce maintenance and logistics costs.

b. Logistics Infrastructure

Industry has been applying machine intelligence technologies to internal logistics problems since the mid-1970s in applications as widely varied as factory automation, computer configuration, production and distribution scheduling, inventory management, and troubleshooting. Machine intelligence, or knowledge-based solutions, have a significant impact on competitiveness – helping business increase human productivity, reduce manufacturing time and costs, reduce transportation and storage costs, improve product quality, and enhance customer service.

Field material handling robotics technology being advanced by the military will provide industry with machines that can rapidly handle cargo or tooling in the 5,000-pound class through large work envelopes in highly unstructured environments.

Industry's push for automated storage and retrieval systems with their increasingly unmanned warehousing and distribution machinery are the essential applications of the ever increasing capability of robotics technology and machine intelligence to both the input and output logistics of, and inseparably from, the automated manufacturing process.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Objectives

Defense-related developmental plans for this critical technology focus on the key issues needed to realize its defense potential, including overcoming technical barriers that limit the application of machine intelligence and robotics to military situations. Such key issues include developing effective knowledge representation techniques, improving the ability of computer-based reasoning tools, enhancing the man-machine interactive environment, and solving a number of mechanical engineering issues. The following technology sets describe major components of the plan and target completion dates:

b. Development Milestones

(1) Knowledge Acquisition and Representation

- Development of generic algorithms for critical military analysis areas (1995).
- Achieve reliable associative memory and sensor-based learning (2000).

(2) Automated Reasoning

- Advanced AI logistics, simulation, and diagnostics support (1995).
- Semi-autonomous systems (2000).

- Battlefield management (2005).
- AI for autonomous weapons and vehicles (2005).

(3) **Spoken Language**

- Real-time, speaker-independent, continuous speech recognition with 5,000 word vocabulary (1993).
- Real-time, speaker-independent, continuous speech recognition with unlimited vocabulary (1998)
- Real-time, speaker-independent, speech understanding for interactive problem solving in constrained domains (1995).
- Real-time, speaker-independent, multilingual speech understanding for interactive problem solving (2000).

(4) **Written Language**

- Accurate routing and retrieval of documents (1996).
- Semiautomatic data base filling from text messages (1996).
- Automatic data base filling from text messages (2000).
- Machine-aided translation of text (1998).

(5) **Man-Machine Interface**

- Adaptive interfaces (1995).
- Pilots Associate (2000) AI-based decision aids.

(6) **Training**

- Language training (1995).
- AI simulation (1995).

(7) **Articulated Mechanical Devices**

- Repair/handling systems (1995).
- Robotic vehicle networking (2000).
- Autonomous vehicles (2005).
- Automated sentries (2005).

2. **Technology Objectives**

Major objectives for this critical technology area are listed in the table below.

Technology Objectives — Machine Intelligence and Robotics

Technical Area	By 1996	By 2001	By 2006
Unmanned ground vehicle	• One operator controls two RCVs	• Robotic combat vehicle (one operator controls five RCVs) • Robot vehicle networking and interfacing family of RCVs	• Substantially expanded autonomous operation of unmanned ground vehicles
Robotic manipulator	• Field demonstration of tank loading	• Light-weight robotic vehicle	• Widespread use of robotics throughout weapon systems
Data rate reduction	• Telerobotic vehicle • Automatic planning and control of assembly from CAD models	• Robotic security patrol with remote display and control • Autonomous capability to reason and react	• Continuing reduction in size and increase in power of data reduction capabilities

3. Resources

Total S&T funding for this critical technology is shown in the following table.

Funding — Machine Intelligence and Robotics ($M)

FY87–91	FY92	FY93	FY94	FY95	FY96	FY97
551	146	142	145	144	144	143

4. Utilizing the Technology

Some of the DoD's most critical problems exist in logistics; current projects focus on efficient and intelligent resource allocation in military transportation and sustainment planning. Additionally, the DoD is investing in the development of robotic material handling systems for logistic applications (such as acquiring replacement parts). Nonlogistics applications also have achieved success to date. For example, the use of fiber optic–guided missiles (FOG–M) offers promise regarding the potential for future tele–operated systems. Tele–operated systems may be used as a force multiplier in which one manned vehicle could control a fleet of tele–operated companion vehicles. Today, DoD has efforts to develop a tele–operated mobile platform (TMP) that can serve as an unmanned reconnaissance platform. Another important application of a tele–operated robot will be the development of Caleb, a small vehicle capable of reconnaissance, surveillance, and target acquisition operations for the infantry. Further research will be directed at improving the man–machine interface for Caleb and developing autonomous capabilities for robots such as Caleb.

The application of expert systems is accelerating due to the commercial availability of shells, software tools to assist in the capture and representation of relevant knowledge and to facilitate the selection of appropriate reasoning mechanisms. This has had the secondary benefit of increasing the in–house technical understanding of machine intelligence concepts; for example, in extensive employee training programs that use expert systems on a daily basis. Over the next decade, the product of DoD's basic research and exploratory development efforts can be expected to affect weapon systems and related command and control. Many of these products are likely to lead to machine intelligence components embedded in larger conventional software systems.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

a. Current Manufacturing Capabilities

Robots play an important role in factories when used in applications such as spot welding and automatic transfer of workpieces. In certain factories, and in all of the domestic automobile manufacturers, significant economic benefits can be achieved for applications that exhibit a large ratio of production time to programming time. Unfortunately, the current capabilities are limited. Machine intelligence (controller technology) will enhance and expand the applications of robots in manufacturing.

DoD investments are geared toward long-term development of new manufacturing technology in the specific area of machine tool-robotic controls, which is not currently taking place at an adequate rate in the private sector. Major developments in this area will help our industrial base and will be of advantage to the defense industry on a long-term basis. Areas the DoD currently is exploring with regard to machine tool-robotic controls include: light scattering for defects, laser triangulation for threads and defect depths, cutting tool fiber optics, neural networks, and cutting tool diagnostics. Our eventual goal is to actively work with domestic machine tool builders in the development of new manufacturing technology and to combine their technical expertise with that of DoD. DoD investments can be used to help leverage additional funding from industry and State government for these projects.

Manufacturing technology programs involving robotic metal welding use advanced sensor systems (such as acoustic emissions, vision, thermal, and gas flow) that can be integrated with artificial intelligence into computer software to control the process. One robotic system provides the means whereby manufacturing technology (generated by modeling and simulation) can be transferred directly to the shop floor via a computer-aided design systems. Other DoD manufacturing technology investments include utilizing robotic arms for assembling wire harnesses that have several different wire types (including twisted pairs); applying inertial measurement techniques to robotic arms; monitoring and controlling plating processes; applying a robotically controlled laser paint stripper to aircraft; and using expert systems to assist in analysis, design, and planning of factory information systems.

b. Current Logistics/Support Capabilities

Other than in the well-structured environment of the factory floor and the automated warehouse, efforts to extend robotic capabilities to the outside world of industrial/commercial logistics have been highly constrained. The development of unmanned machines to work in the great outdoors, except in those cases where hazards to life and special military or other governmental needs must be met, can be expected to lie at the end of a long evolutionary process that provides incremental aids to "unburden" the machine operator under the pressure of the market place. Possible exceptions that the military should closely watch for leverage include: (1) the increasing capability in container handling, tracking, and manifest automation to provide "inventory-in-motion" and improved supply node efficiencies, and (2) the development of machine-compatible packaging and load restraint concepts.

2. Projected Industrial Capabilities

a. Projected Manufacturing Capabilities

DoD has a number of initiatives in place to continue support of machine intelligence/robotics in the longer term, primarily through the manufacturing technology program. The Air Force "Next Generation Controller" project is intended to develop an advanced computer numerical control (CNC) controller with a flexible open architecture to help U.S. manufacturers recover some of the market share lost to imports. The Army's focus in establishing thrust areas or centers of excellence for machine tools and welding of metals will utilize advanced sensor systems, such as acoustic emissions, vision, thermal and gas flow that can be integrated into artificial intelligence applications. A sample of planned manufacturing technology efforts for the Navy include: robotic airframe assemblies: robotic inspection of complex composite shapes; robotic laser paint stripper; plasma arc–CNC machining technology integration, and enhanced propulsor manufacturing.

The DoD Defense Production Act Title III program potentially could foster growth in areas where the industry must retain domestic capabilities to support future technology applications deemed essential for national security. In addition, DoD has contacts with other U.S. government agencies regarding development of machine tool control technology. These contacts provide theoretical knowledge, especially in software development, which has been usefully combined with the practical applications available within DoD, and help provide a broad basis for future manufacturing capabilities and development thrusts.

b. Projected Logistics/Support Capabilities

Machine intelligence in knowledge–based planning and scheduling systems will enable planners to do true "what–if" analysis — modeling and analyzing many different scenarios and evaluating the impact on such critical factors as lead time, inventory, costs and capacities. The result is better utilization of expensive resources through better planning. Knowledge–based planning and scheduling systems will close the gap between upper–level planning and production floor operations by helping manufacturers make complicated facility planning and production scheduling tradeoffs based on overriding business objectives.

Each of the elements in the paragraph above have a direct military logistic counterpart that ultimately impacts the individual soldier. Machines that can think and plan, and machines that can autonomously execute those plans, will emerge worldwide to meet special needs in both the industrial and military sectors. The ability of planners to track these diverse undertakings and maximize their effectiveness in both worlds will probably have to feed on itself and employ and aid the very best in machine intelligence.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

Extensive robotics/machine intelligence research is conducted by the Bureau of Mines, National Aeronautics and Space Administration (NASA), and the National Institute of Standards and Technology (NIST). Work also is sponsored at universities by the National Science Foundation (NSF). Knowledge–based systems and neural nets are under study at DoE laboratories and robotics is increasingly used in handling hazardous materials in nuclear processing.

While some of the efforts are DoD oriented, development of robotics/machine intelligence for use in special applications (mining operations, operation in hazardous indoor environments, and manipulator arms and appendages) is being pursued. Research in command and control, remote operation, and vision technology may be leveraged for DoD efforts.

NIST effort includes:

- Knowledge acquisition and representation: Within the automated manufacturing program, NIST is progressing from finite state machines where all contingencies must be dealt with a prior; to knowledge-based systems which can both learn from experience and adapt to circumstances from knowledge of a more general nature. This work requires the acquisition of knowledge now embodied in human experience and the expression of that knowledge in machine accessible form, use of "fuzzy logic," and new control architectures.
- Automated reasoning: NIST is investigating the use of neural networks for process control and has a prototype system in place for the control of metal atomization.
- Articulated mechanical devices: As part of a wide ranging program in robotics, NIST is experimenting with devices ranging in size from small mechanical deburring tools to construction cranes with variable and software controlled compliance in three dimensions. With such systems the stiffness of the tool can be made much greater than the structural stiffness of the supporting "arm."

NSF supports research to develop the knowledge needed for advanced robotic and other intelligent systems. Research topics include pattern recognition, machine vision, speech and language understanding, advanced sensors, robot dynamics and control manufacturing technology, automated reasoning and task planning, and knowledge-based systems.

2. R&D in the Private Sector

Machine intelligence and robotics efforts in the United States are robust, with new enterprises coming to market constantly. On the other hand, relatively few U.S. companies are developing robots for commercial applications. DoD-funded research in universities includes machine planning and reasoning, knowledge acquisition by machine, knowledge representation by machine, and natural language understanding by machine. Research activity in neural networks has increased, particularly in the past three years, with most efforts still in universities but with work significantly moving toward industrial research laboratories and application groups.

About 15 to 20 start-up companies have been formed to exploit the technology in the past two years, with a market of approximately $20 million, primarily for supplying R&D efforts and focusing on computer hardware and software tools for research and prototype development. A few commercial applications have been developed, including a decision aid for processing mortgage loan applications, a device for reading hand-printed amounts on checks, and an assembly line parts inspection application.

Several companies have substantial speech and text processing research programs. These include AT&T, Bellcore, IBM, Texas Instruments, and Xerox. However, the research conducted in these companies is focused on specialized markets and does not directly address critical DoD needs.

U.S. university basic research in the area of adaptive real-time information processing and manipulator control offers significant opportunities for advances in technology leading to the implementation of a wide variety of intelligent (autonomous) and other robotic systems. The control of the dynamic performance of robotic manipulators that are programmed to follow certain desired trajectories remains a difficult and complicated task, because the manipulator may be compliant in its joints and links. Therefore, progress in the design, construction, and operation of manipulator arms will be realized through the development of appropriate mathematical modeling and analysis techniques and the execution of key experimental investigations. These activities are essential to achieve a thorough understanding of the kinetics, dynamics, stability, and control of future manipulator systems made from modern lightweight materials, such as laminated composites. The university community possesses the necessary skills, knowledge, and capability to successfully accomplish these tasks.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

The table on the following page provides a summary comparison of the United States and other nations for selected key aspects of the technology.

Ongoing international research and development indicates potential international capabilities to contribute to meeting the following challenges and goals:

- Development of specialized techniques for AI applications of advanced processing architectures;
- Practical telecontrol of military vehicles;
- Application of advanced structural materials to robots having high dynamic loads or required to operate in hostile environments;
- Integration of smart sensors and improved actuators.

a. General

Principal cooperative opportunities will exist with NATO countries, especially in the area of software algorithms and image/signal processing applications, and with Japan in applications of optical neural net research.

The United States has had a commanding lead in computational capabilities, but the lead is being diminished. Japan and, to a lesser extent, some of our European allies have made significant advances in the industrial application of such technology. Much of this R&D is transferable between civilian and military applications.

b. Robotics

Japanese robotics R&D has benefitted from a 7-year joint project formed in 1983 under the Ministry of International Trade and Industry (MITI) to advance Japanese robotic R&D in the areas of nuclear power plant clean-up, firefighting, and undersea construction. The MITI project addresses sensors for sight and touch; vision control; versatile robot arms capable of both high precision and high-weight capability; efficient motors for robots; and low-weight, high-strength materials for robots. During the MITI project, for example, Toshiba, Fujitsu, and NEC have worked on vision systems; Fuji Electric Company worked on manipulators with both strength and delicacy; Ishikawajima-Harima Heavy Industries Company created a metal skin for a firefighting robot, which included sweat glands: Fanuc, Ltd. built powerful actuators for robot appendages: Hitachi is still working on a fourlegged locomotion system: and Komatsu, Ltd. is continuing work on hydraulic masculature which runds on a sea water.

MITI is also planning to sponsor a 10-year, $1 billion research program on "the factory of the future" to begin in 1991. The aim of the project is to create computer controlled factories, and various individual projects will try to link emerging technologies with robots, for example, using photonic sensors on robots equipped with artificial intelligence. Japanese entities expected to participate include Tokyo Metropolitan University, Hitachi, Toshiba, Toyota, Nissan, Fujitsu, and NEC, as well as about 75 others. MITI hopes to contribute robotics technology and mass production technology to the project in return for American software expertise and German and Swiss precision machinery craftsmanship.

Another MITI program planned to start during 1991 is a 20 billion yen program to develop space robots for fabricating or repairing structures in space. The program is called "Research on Space Work Systems" and is to be administered by the Agency of Industrial Science and Technology as a large-scale survey. The intelligent space robots are planned to be controlled from a space station or from earth. The robots are intended to be as capable as humans for assembling structures in space, handling parts, and repairing circuits.

The Japan Atomic Energy Research Institute (JAERI) began a 10-year program during 1987 to develop technologies for intelligent robots and intelligent nuclear plants. The project consists of technologies for a knowledge-based system, robot vision, robot kinematics/ kinetics, plant geometry base, dose evaluation, and a high speed Monte Carlo machine. During 1990 the program achieved a simulation of a biped locomotion robot in JAER's JPR-3 nuclear plant and simulation of the robot going down a flight of stairs.

In independent projects, Shimizu Corporation manufactures robots that can assemble steel girders, smooth concrete slabs, and spray-paint walls. Scientists in the Toshiba Energy Science and Technology Laboratory are building snakelike robots which can move objects, and "master-slave" robots (arms controlled by a human wearing an electronic control glove) for heavy lifting. The Tokyo Institute of Technology has been experimenting with mobile robots using various configurations of legs and wheels. Waseda University is currently working on the second version of a robot with such complex articulation that it can play classical music on the piano. Kajima Corporation has built an excavation robot for building tunnels and a tile-testing robot. The Transport Ministry Port and Harbor Research Institute is attempting to develop a robot which can inspect sea-floor building sites. Hitachi has formed a collaboration with a Yale scientist to build robot arms which have a hardened skin studded with "smart" sensors -- the arm is able to react to a perceived obstruction. Matsushita Electric Industrial Company is the market leader in Japanese robotics. Komatsu had developed an industrial robot that installs panels up to 1,100 pounds in the exterior walls of buildings. An eight-company consortium led by Tokyo Electric Power Company and Toshiba Corporation developed an inspection and monitoring robot for nuclear power plants. Japan's experience in industrial robots, and its underlying technology base in "fuzzy logic," could make significant contributions to the allies' capabilities if both sides agree to cooperate in robotics technology.

As examples of joint ventures with U.S. firms, Fanuc and GM created GMFanuc for automotive systems. Matsushita has an arrangement with Cincinnati Milicron to distribute welding robots. Yaskawa Electric and Hobart have established Motoman, Inc. for marketing arc-welding robots in the United States. Japan's experience in industrial robots and its underlying technology base in associated computer science and technology could make significant contributions to the joint venture partners' capabilities if both sides agree to cooperate in robotics technology.

Summary Comparison — Machine Intelligence and Robotics Relative to the United States

Selected Elements	USSR	NATO Allies	Japan	Others
Development of specialized techniques for AI applications of advanced processing architectures	□	□□□ ○	□□□ ○	
Practical telecontrol of military vehicles	□	□□□ ○	□□	
Application of advanced structural materials to robots (having high dynamic loads or required to operate in hostile environments)	□	□□□ ○	□□□□ ○	
Integration of smart sensors and improved actuators	□	□□□ ○	□□□□ ○	
Overall[a]	□	□□□ ○	□□□□ ○	□□ Finland, Israel, Sweden

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

- □□□□ broad technical achievement; allies capable of major contributions
- □□□ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
- □□ generally lagging; allies may be capable of contributing in selected areas
- □ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

- \+ Foreign capability increasing at a <u>faster</u> rate than the United States
- ○ Foreign capability increasing at a <u>similar</u> rate to the United States
- — Foreign capability increasing at a <u>slower</u> rate than the United States

The European Community has nearly completed the second phase (1987 to 1991) of the European Strategic Program for Research in Information Technology (ESPRIT), which is addressing natural language understanding, computer vision, robotics, machine learning, computational logic, expert systems, and AI hardware/software developments. Part of the ESPRIT project involves combining these technologies and setting standards for a European "factory of the future."

France has emerged as a dominant force in European software and as a world leader in artificial intelligence. French research is beginning to move into industrial applications. Under the European Research Coordination Agency (EUREKA) program, they are also developing capabilities for real-time threat analysis and crisis management that could be, directly applicable to battle management and C^3I applications. This effort also involves Norway. In the EUREKA program segment for flexible automated assembly systems (FAMOS), the UK is falling behind: e.g., has only three current AI/robotics related FAMOS projects. One of these consists of producing a robot arm which can manufacture different products on the same assembly line. The UK companies involved are Bristol Polytechnic, Britax, Salford University, Hull University, Crocus (robot manufacturer), and Mari (sensor manufacturer); other collaborators are the Austrian company Alcatel-ELIN, the French company Apsis, and the Italian company HS Elettronica. Luxembourg had one project — a robot brick layer — and the Netherlands are researching robotic sensors and controls.

Independent of the FAMOS project, the company Morfax, Ltd. Worldwide in Britain had developed a bomb-disposal anti-terrorist robot. Hydrobotics Engineering Canada, Inc. is involved in sea research robots. The Institut fur Informatik II of the Universitat Karlsruhe in Germany has been researching design of intelligent sensors and controls for industrial robots since 1986. Scientists there expect to develop a high order programming language for assembling robots, simulate assembly networks, design a multiprocessor robot controller, establish rules for integrating robots into computer-aided manufacturing systems, and develop vision systems and multisensor systems for manipulators. Germany is considered to lag only France in the European robotics production market.

Exemplary of the capabilities of our NATO allies are the collaborative efforts between NASA and the German Aerospace Research Establishment (the DFLRV). This effort includes several robotics projects, with a stated goal of attaining a ten-fold reduction in weight over present technology. Germany is also active in research in certain aspects of military vehicle control.

The Soviet Union lags behind the United States significantly in machine intelligence and robotics. They do have a good theoretical understanding of the area and can show creativity in applying the technology to selected space and military applications. Soviet R&D on artificial intelligence (AI), under the auspices of the Academy of Sciences of the USSR, includes work on machine vision and machine learning. The value of machine intelligence to battlefield operations as well as to the domestic economy has been recognized by the Soviet government.

At the Technical University of Lublin in Poland, researchers are studying fatigue strength of optical fibers used for vision in dynamic conditions of intelligent robotic systems. Several Pacific Rim countries are entering the field of robotics. Korea and Hong Kong have already established a robots industry. Singapore is making a major R&D push to have such high technology industries as robotics and artificial intelligence established by 1993 (5 years from 1988 announcement).

c. Machine Intelligence: Neural Networks

The Japanese Institute of Technology and Hamamatsu Photonics have jointly developed a rudimentary optical neural computer to explore image processing tasks. The goal of the project is to develop "intelligent sensors." Japan has also produced what has been described as the first optical neurochip, consisting of a 32 x 32 element array implementing 32 neurons. This chip, integrated on an 8mm square (GaAs) substrate, is based on an advance in optical bonding that will allow the chip to be used more readily with other integrated circuit devices and on printed circuit boards. The University of Tokyo and Hammamatsu Photonics are working together to develop the "optical association," which is an optical associative memory device with learning capability, to use with neural network computer architecture.

Interest in neural nets within NATO countries is limited and is primarily associated with specific applications. The Netherlands and Germany have expressed an interest in neural networks, primarily in association with their work in 2–D/3–D imaging (which is, in some areas, advancing more rapidly than that of the United States and Japan). The UK also has expressed an interest in the area for radar processing applications. Its Alvey program has a major effort in adaptive user interfaces that may provide benefit to future neural net applications.

An ESPRIT II project called Pygmalion began in January 1989 and addresses broad issues related to neural network development tools and applications. A stated aim is to demonstrate the potential of neural networks to real–world industrial problems. A sampling of the research groups involved in this effort include Thomson–CSF (image and acoustic signature processing and high level language development); Computer Technology Institute, Greece (cellular automatic tools and 3D pattern recognition); and the Universidad Politecnica de Madrid, Spain (speech processing).

Outside of NATO and Japan, interest and capabilities in neural nets appear limited to specific applications such as speech and image processing and potential application of the technology to remotely piloted vehicles (RPVs). The USSR has had neural net models since at least 1988. Finland (Helsinki University of Technology) and Sweden (Royal Institute of Technology, Stockholm) have research efforts in the use of neuro–computing to pattern recognition for speech and image processing. Israel is among the world leaders in operational use of military RPVs. Opportunities for cooperation in specific niche technologies may be realized in these areas.

2. Exchange Agreements

There is a significant level of exchange activity in the diverse technologies of machine intelligence and robotics. Various NATO programs provide the United States with a mechanism for exchanges of general information regarding potential application of these technologies.

The Technology Cooperation Program (TTCP) has a specific exchange in the application of AI–based aids for military operations and provides a vehicle for a range of applicable exchange activities under the variety of programs for which AI is an underlying technology (e.g., in undersea warfare, monitoring and diagnostics, signal and image processing, electronic warfare, training, guidance and control, etc.)

Each of the Services also has exchanges, primarily with NATO, in areas of specific interest. These provide mechanisms ranging from general exchanges in AI research to exchanges in a variety of specific applications, including pattern recognition for smart weapons, control and operation of RPVs, implementation of smart cockpit techniques, and battlefield robotics.

5. SIMULATION AND MODELING

5. SIMULATION AND MODELING

A. DESCRIPTION OF TECHNOLOGY

A computer model is an analog, digital, or hybrid representation of an entity (object, system, activity, process, or situation) including, as appropriate, subsystems, components, and their interrelationships. A simulation is an implementation of a model or set of models. A hybrid simulation combines computer representations with actual equipment, prototypes, or field trials. Simulations are used to better understand the collective behavior of larger systems ("systems of systems") operations in various situations and under various scenarios.

Our capabilities in simulation and modeling have expanded rapidly in the last several years due to great increases in computational power, computer networking, computer visualization, and software. This has led to vastly expanded opportunities to employ simulation and modeling throughout the acquisition, development, testing, deployment training, and logistical support phases of all military systems. Simulation systems are able to provide, capture, and reduce ever more data, expanding these activities in both scope and detail.

The four components — computers, networking, visualization, and software — are each critical technologies which are separately described in this Plan. Military simulation and modeling is quite dependent upon continuing advances in these areas. As a particular application of these critical technologies, it integrates them in a particular fashion and builds its own software products. This integration and applications software activity — simulation and modeling technology — is the critical technology discussed in the technology plan.

Critical technology challenges in simulation and modeling span the improved management of complex battlefields (including camouflage, deception, nuclear conflict), training of personnel (especially in complex military environments), and improved industrial design and production.

Technology Sets in Simulation and Modeling Technology

- Numerical solutions
- High speed graphics
- Non-linear computational problems

B. PAYOFF

1. Impact on Future Weapon Systems

a. Weapon System Performance

Cost savings and/or greater value are realized in recognizing the opportunities to employ new technologies, in defining requirements, in developing acquisitions, in testing and evaluation for both development and operations. With the development of better human interfaces, simulations support training, the development of doctrine, and studies of operational effectiveness. Using simulations which cover larger systems and scope, the support and logistic aspects of any new or newly-employed systems can be studied.

Simulation and modeling technology can be and is applied to every major DoD weapons development program to reduce cost both in design and production, to improve performance, and to improve diagnostics, maintenance, and "life-time" logistic support of fielded system. Simulation aids in the training of personnel, both in the operation of equipment and then in the use of that equipment in larger units as fighting teams. This results in improved command, control, communications and intelligence on the battlefield at all levels of conflict.

For example, training cost effectiveness and safety can be significantly increased by providing a sufficiently realistic interactive simulation of tanks, armored personnel carriers (APCs), portable weapons, fighter/attack aircraft, helicopters, surface combatants, and other systems. The capability for linking existing training devices worldwide will provide a level of integrated training that goes beyond the teaching of individual skills. Newly proposed systems (such as vision devices, antitank weapons, and antihelicopter weapons) can be simulated digitally so that the utility of given technical and human-centered parameter requirements can be assessed before hardware is built. The use of simulation and modeling in the systems design process will enhance the operational suitability and effectiveness of virtually all human/machine systems, whether being initially procured or being modified.

The payoff for large-scale maneuver simulation, in terms of improved combined arms training at reduced costs, is enormous. Simulation and modeling of the combat environment involves the assessment of the effect of critical parameters (such as weapons and force effectiveness) on battlefield engagements. Simulators and models are also used to estimate human factors in this environment, including behavioral modeling of crew performance, development of computer-aided decision making aids, and design of automated controller aids for battle simulations.

Simulation and modeling concepts are applied to the assessment of sensor, observer, and processor performance to represent realistic military operational environments, ranging from digital imagery analysis to predictions of the physical effects of environmental influences (such as temperature or weather conditions) upon weapons systems and prototypes. This critical technology can have particularly heavy application in difficult operating environments such as the ocean, where environmental influences are not well understood due to the lack of available temporal and spatial information in regional or global areas. (See the discussion of Weapon Systems Environment for further details). Model simulations will help to optimize the effectiveness of limited and costly at-sea experimental observations. Also, nuclear effects simulation is a critical element in estimating the vulnerability of our weapon systems and supporting C3I during a nuclear weapons exchange.

In the electronic warfare (EW) area, a major payoff is the development of a coordinated force-on-force EW simulation capability that can provide assessment within the integrated combat process. The mid- to long-term payoff of this capability will be a coordinated combat management process capable of responding to immediate, mid-term, and long-term objectives. Integrated modeling techniques can be used to run individual software modules in a coordinated battle force EW simulation. The goal of these modeling and simulation efforts is to prescribe coordination procedures for combined electronic countermeasures against threats throughout the spectrum of conflicts.

b. Weapon System Logistics

Weapon systems are becoming more difficult to diagnose and troubleshoot because of their increasing complexity. Future applications of simulation and modeling technologies should focus on logistics support tools for fielded systems that address this problem, while at the same time reduce operating costs, increase maintenance effectiveness, and enhance systems performance. Logistics simulation and modeling should address both near-term and long-term "life support" issues to ensure weapons systems remain efficient and effective throughout their anticipated life cycles.

Enhanced simulation and modeling techniques will be used to establish reliability and maintainability needs for given environmental and/or operational constraints. They will be essential for establishing standards and test architectures. These capabilities will permit automatic test pattern generation from model-based product descriptions. Test program set development as well as update implementation times will be substantially reduced.

Products utilizing advanced simulation and modeling technologies will include interactive training devices, automated technical manuals, and highly accurate test and diagnostic tools. These tools will have wide access to distributed data bases and information sources, thereby expanding "what if?" analyses capabilities. These products will become portable and accessible to weapon system maintainers in operational field environments.

c. Integration

One commanding theme of today's simulation and modeling is integration. It is now practical and extremely rewarding to employ one consistent set of simulation tools across the spectrum of activity from new concept evaluation, through research, development, acquisition and testing, through human factors engineering and training, into near-term and long-term logistics and supply support for fielded systems, and all along the way to respond to difficulties as they develop.

2. Potential Benefits to Industrial Base

DoD efforts in simulation and modeling offer many opportunities to transfer technology from weapon system R&D to the defense industrial base through improved training, design, manufacturing, and exploration. For example, the development of advanced environmental ocean simulation models will allow the industrial base to develop improved sensors that exploit advanced instrument technology to combine limited *in situ* data with existing and forecasted data. Such development can help benefit undersea or geophysical prospecting, petroleum exploration, and other applications.

DoD's industrial-related simulation efforts (designed to help produce military systems of significantly greater usefulness) can also contribute to the U.S. industrial base. Current DoD efforts in this area include developing engineering trade-off decision simulations such as the transient radiation effects on electronics (TREE) program (which simulates the "hardening" processes needed by microcircuits in a nuclear radiation environment) and diagnostics of complex systems through modeling series of alternative situations until they match the observed failure modes.

The fields of human factors engineering and training technology are rapidly expanding and have many developments that involve simulation and modeling. A few developments relevant to the industrial base include:

- Human factors engineering used to increase usability and reduce errors. Many human issues can impede system success if they are not studied and considered early in the development process.
- Virtual prototyping of systems, using computers and involving actual target population members in tests, to reduced the cost and speed

arrival of the final product. Virtual prototyping can reduce the time from adoption of a weapon to assimilation of the weapon into the force in accordance with appropriate employment doctrine.

- Application of new technologies to enhance our ability to provide realistic training (including feedback) tailored to the student's needs. These technologies include digital audio, compact disk read only memory (CD ROM), High Definition Television (HDTV), videodisc, tutoring modules, simulation-based training, holography, 3-D television, and speech recognition.

- New training strategies, primarily derived from work of cognitive psychologists, to provide insights into performance problems. These strategies reduce the time it takes for a novice to become an expert performer, increasing the cognitive level a student may attain in training settings, and increasing the positive transfer of training to the real world.

- Simultaneous engineering, a process that integrates design and manufacturing and support processes of any product. If manufacturing and human-centered supportability aspects of the design are considered up front, product design can be altered as required before the design is frozen (thus alleviating costly downstream changes required for production). This up-front consideration of manufacturing processes allows greater emphasis on efficiency, increased quality, and reduced cost. Simultaneous engineering is a dual-use technology that can be applied to non-defense-related industrial design as well as to weapon system design.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

Military simulation and modeling technology encompasses a widely diverse collection of research and development programs. In this section, these programs are divided into three application areas: battle management, training, and product development.

a. Complex Battle Management

(1) Objectives

Simulation and modeling are used increasingly to evaluate more sophisticated systems in highly hostile environments. Because of this it will be necessary to develop even more high-fidelity models in real or faster-than-real time, in order to: test and evaluate systems; develop strategies and tactics; demonstrate capabilities; and ensure reliability, survivability, and effectiveness without expending actual equipment and personnel. The battle management technology set is divided into areas of hardware (distributed computation), software (simulation codes), and the integration of real-time hardware and software. R&D activities through FY 1997 in support of these technology objectives include the development of:

- Distributed and parallel computation (hardware)
  - Effective parallel object-oriented database system.
  - Real-time parallel Ada.
  - Greater-than-10-gFLOPS simulators.

- Simulation codes (software)

  500 thousand lines of code in real time

  Establishment of simulation V&V technology

- Integration of real-time hardware and software

  Fiber-optic networks for distributed real-time systems.

(2) Development Milestones

- Distributed and parallel computation (hardware)

  Hardware suite for SDIO at the NTF, operational FY 1991

  Multilevel security fault-tolerant operating system, FY 1995.

- Simulation codes (software)

  Completion of initial ground-based surveillance radar model, FY 1991.

  Level 2 SDIO end-to-end simulator, complete FY 1993.

  End-to-end IR sensor simulator, FY 1994.

  Towed-array acoustic self-noise model, completed FY 1994.

- Integration of real-time hardware with software

  Ground-based radar propagation simulator demonstration, FY 1991.

  Demonstrated initial long wavelength infrared clutter simulator, FY 1992.

  Upgraded optical nuclear clutter specifications, FY 1993.

  Completion of space-based radar propagation simulator, FY 1995.

  Completion of tactile gloves and helmet displays, FY 1996.

b. Training in Complex Military Environments

(1) Objectives

Simulations and models are increasingly used for training and development of human-in-control support systems. In addition to the obvious requirement for real-time simulations of adequate fidelity, there will be a need for faster-than-real time to permit on-line diagnostics and the ability to provide "what if?" support. This technology set therefore is divided into two subsets — high-speed graphics and man-machine interfaces. Technology objectives for each subset are:

- High-speed graphics

  Development and promulgation of graphic standards.

  Integration of high-speed hardware and software.

  Use of high-speed screens using 64 Mbit chips.

- Man–machine interfaces

  Increasing use of AI and expert systems in man–in–the–loop displays.

(2) **Development Milestones**

- High–speed graphics

  Development of carrier–based weapon system mission rehearsal capability, FY 1991.

  Completion of a PC–based radar simulator for training, FY 1994.

- Man–machine interfaces

  Demonstration of complex AAW scenarios for AEGIS training using expert systems, FY 1992.

  Application of AI tutoring to computer–based instructional systems, FY 1993.

  Testing of under–ice piloting trainer, FY 1993.

c. **Design and Production**

(1) **Objectives**

Simulation and modeling technology is useful in the design and production of component parts. Specific applications include modeling methods for production processes as well as preliminary validation of compound designs in a variety of simulated environments. Many of the objectives listed above in the first two technology sets pertain. In addition a subset of design tools is identified for this technology set. Specific objectives include:

- Development of high fidelity simulations on PC or production computers.
- User–friendly interfaces of complex code for production personnel.

(2) **Development Milestones**

- Development and application of sophisticated numerical methods for nonlinear processes.

2. Technology Objectives

Technology Objectives — Simulation and Modeling

Technical Area	By 1996	By 2001	By 2006
Complex battle management	• Integration of battlefield simulation into a battle management test bed, to have a test and evaluation approach for new planning and decision aids, pinpointing deficiencies in existing aids as the threat changes, and evaluating the effect of changes in our own doctrine, tactics, weapons, etc.	• Application of knowledge-based techniques for design of complex systems including large software systems and battle management simulations • Demonstration of C^3I workstation • Use of actual world technologies, selection, and training	• Substantially improved battle management, decision aids, human factors design, and cost-reduction techniques
Training in complex military environments	• Increased use of AI and knowledge-based systems in display generation	• Order of magnitude cost reduction for training and human factors design • Fully integrated real-time simulations with man-in-the-loop capability	• On-line diagnostics and "what-if" capabilities
Industrial design and production	• Modeling performance of hypothetical designs to help make trade-off decisions for optimal design	• Diagnostics and prognostics by modeling alternative situations	• Substantially improved cost effectiveness, planning, and design

3. Resources

Total S&T funding is shown in the table below.

Funding Simulation and Modeling ($M)

FY87–91	FY92	FY93	FY94	FY95	FY96	FY97
1230	334	343	340	335	344	344

[5] Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

The United States has been a leader in development of simulation and modeling. In manufacturing, many software packages are available that can accurately model and simulate production flow in discrete parts manufacturing. They run on most brands and sizes of computers and permit a number of industrial engineering analyses for efficiency and process improvements.

Simulation permits establishment of process parameters through computerized methods, rather than through trial and error effort on actual plant equipment. In addition, simulation permits creative exploration of process alternatives in the product design stage. Thus, product design, manufacturing, and human-centered supportability issues are considered simultaneously or concurrently (hence the terms, simultaneous engineering and concurrent engineering).

2. Projected Industrial Capabilities

Domestic manufacturing advances will depend largely on the advances of computer and software technologies. Industrial simulation will require large increases in both processing speed and memory size, as well as the fundamentals associated with advanced technologies such as artificial intelligence. Simulation and modeling of metalworking processes is a key to successful development of processes for new, hard-to-work alloys such as aluminides and rapidly solidified powders. For example, simulation, in conjunction with an experimental development program, is necessary to establish processes for forming titanium aluminides for future aerospace applications.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

DoE is involved with, or is researching, future research and development efforts in the following areas:

- Virtual prototyping to enable engineers to visualize and test new components.
- Remote instruction for collective training and high cognitive level learning to replace or enhance schoolhouse learning experiences.
- High technology education, where students learn complex realistic problem solving through collective training and learning experiences in the classroom (made possible by rapidly accessing multiple data sources).
- Simulation-based training, where students can practice high-risk scenarios with expert, immediate feedback in a cost-effective configuration.
- New weapon system design, including human factors and training considerations via computer simulation, for the purpose of determining design effectiveness, learning constraints, and cognitive overload considerations. These new design practices also

permit experimentation prior to full-scale development of the new system.

- Specifying requirements and design criteria for new C^3I systems in real-time environments.

Other areas in which computer modeling has significantly affected U.S. R&D programs include weapon design and effects (nuclear, conventional, and chemical); prediction of effects of vibration, acceleration, and ionizing and non-ionizing radiation on man; and understanding interactions among low observables, materials, and geometries with electromagnetic radiation.

NSF supports research in virtually all areas of science and engineering in which simulation and modeling play a significant role. Systems of interest range in size from galaxies and star clusters to collections of interacting atoms and molecules. The recent acceleration of computational technologies has provided new focus on the development of algorithms and research on means and methods of handling and representing data, including graphics and visualization.

Ongoing programs in mathematics and computer and information sciences support basic work on developing algorithms for simulation and modeling, prototype software development, and simulation and modeling of communication systems. Programs in the physical sciences, biological science, geosciences, and engineering support research in simulation and modeling of physical systems and materials of direct interest to investigators in those fields.

NASA has active programs in simulation and modeling to reduce the risk and cost associated with many of its agency missions. The most visible example of this is the Ames Research Center's Numerical Aerodynamic Simulation Facility (NAS) which supports aerospace vehicle design and validation. Augmented by wind tunnels, NAS allows rapid evaluation of aerospace vehicle design concepts throughout the required flight envelope without a costly commitment in airframe development and without risk to human life and property.

Similar efforts are funded for propulsion system design and fabrication, validation, aerospace materials, and large, space-based structures evaluation.

A more recent trend in NASA's use of simulation and modeling is the creation of large computer models to represent systems too large and complex to analyze any other way; for instance, coupled ocean-atmospheric interactions or galaxy creation and evolution.

Finally, since its inception as a civilian space agency, NASA relies on simulation and modeling to evaluate, refine, and successfully execute its very large, complex, and tightly coordinated space flight missions.

2. R&D in the Private Sector

Industry has a substantial investment in the development of improved real-time simulation technology for training, as well as for weapon system development. For example, all major EW system developers produce engineering simulations prior to and during hardware design and development. These simulations are generally unique to the planned system development and not related to more generic simulation technologies being developed by the Services.

Substantial DoD-sponsored university research is underway to optimally model a wide range of processes, develop robust and efficient computer algorithms (based on the underlying theory), and employ high-performance parallel computers to exercise these algorithms. Computational science is now emerging as a discipline in most major universities.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

Internationally modeling and simulation are applied to a wide range of diverse applications. As the complexity and costs of hardware development increase, designers in all fields worldwide will begin to depend more heavily on simulation and modeling. The table on the following page provides a summary comparison of the United States and other nations for selected key aspects of the technology. Principal cooperative opportunities will continue to exist with NATO countries, especially with the UK, Germany, and Canada, all of whom have substantial efforts. Ongoing international research and development indicates potential international contributions to meeting the challenges and goals identified:

- Developing numerical techniques for modeling of non-linear processes on advanced computing architectures;
- Developing and empirically validating physical models of materials (including material reaction to extreme conditions);
- Effectively applying advanced computing architectures to real-time and faster-than-real-time simulation of complex situations/ environments.

Japan's capabilities in computing and industrial process control offer promising cooperative opportunities in those areas. In general, however, Japan trails the U.S. development of empirically validated engineering data bases, specific to military systems, that are required to do effective modeling.

Many NATO countries, though lagging in certain aspects of modeling, have led the way in producing the hard data with which the models are validated and improved (e.g., the UK's research in chemical defense). Thus, a critical interplay exists between selected modeling communities and their experimental counterparts in other countries.

Secondary opportunities for cooperation exist in niche technologies related to modeling of nuclear and solar power (Italy) and modeling of particle accelerators. In addition, the widespread effort in algorithms for parallel processing, such as that in the Netherlands (described in the section on parallel computer architectures) may contribute to advances in numerical methods in computational fluid dynamics and hydrodynamic modeling.

Many other countries are active in modeling power and transportation systems. These programs are not, however, considered leading candidates to contribute to significant advances beyond existing U.S. capabilities.

Summary Comparison — Simulation and Modeling

Selected Elements	USSR	NATO Allies	Japan	Others
Development of numerical algorithms for modeling of non-linear processes on advanced computing architectures	□□	□□□ ○	□□□ ○	
Development and empirical validation of physical models of materials (including material reaction to extreme conditions)	□	□□	□□□ ○	
Effective application of advanced computing architectures to real-time and faster-than-real-time simulation of complex situations/ environments	□□	□□	□□□□ ○	
Overall[a]	□□	□□□ ○	□□□ ○	

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□ broad technical achievement; allies capable of major contributions

□□□ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions

□□ generally lagging; allies may be capable of contributing in selected areas

□ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

+ Foreign capability increasing at a faster rate than the United States

○ Foreign capability increasing at a similar rate to the United States

— Foreign capability increasing at a slower rate than the United States

Simulation and modeling as a generic field is established worldwide in many civilian applications. Primary applications are found in modeling large complex systems, most notably power (including nuclear power as an important subset), transportation, and telecommunications. These areas are of only peripheral interest at present; however, they could produce advances in software techniques for massively parallel machines that could be transferred to other problems.

Driven by the same economic considerations as the United States, NATO allies are advancing computer modeling and simulation technology. With the exception of Japan, most nations lag behind the United States in their capability to manufacture high-speed scientific computers. However, there is no restriction to their purchasing these machines. Various national and multinational R&D ventures by our allies may focus on targets of opportunity that would also enhance their overall capability.

Within NATO, the UK is active in a number of areas of interest, including computational fluid dynamics and modeling of complex communications networks. British companies — Ferranti, Alvis, British Aerospace, Marconi and Weston Simfire — are currently involved in research and production of various simulation and modeling products. A number of other NATO countries have ongoing efforts relating to various aspects of modeling spacecraft control and thermal management.

Germany uses simulation to explore use of an automatic tactical fighter director with integrated fire-flight control systems for automated air-to-air combat and is active in simulation supporting the European Fighter Aircraft.

Canada is a world leader in dynamic training simulation and is contributing presently to the LH combat mission simulator. Their leading simulation firm, CAE Industries, Ltd. recently acquired four of the five simulation divisions of the United States firm Singer. France has produced six-degree-of-freedom simulations of the Puma SA 330 helicopter and the WS 13 Lynx. Specific efforts of interest include improvements in computer-generated imagery, which are reportedly adequate to simulate real-time flight dynamics with realistically textured objects in simulated day, night, and dusk conditions. The ability to do real-time dynamic imagery with detailed texture adds significantly to the training capabilities. This capability is characteristic of the state of the art in U.S. combat mission simulation (as in the AH-64 weapons system simulator). The UK is developing and using innovative techniques for real-time display that may help to alleviate troublesome time-delay effects in aircraft simulators.

The USSR has demonstrated a strong capability in modeling wave-flow dynamics and turbulence, and their data assimilation efforts for purposes of ocean simulation probably lead those of the United States. Soviet researchers are very capable in the simulation and modeling of aviation and space systems. The United States maintains superiority with respect to data for purposes of modeling (prediction) and computational hardware and software for simulation and modeling.

The USSR uses simulation and modeling extensively for wargaming exercises and weapon development. Although the Soviets trail the United States in computational capabilities, specifically in large-scale computers and graphics workstations, they nonetheless have a thorough understanding of the subject matter. In some applications, such as wargaming, their knowledge base of the subject matter may equal or lead that of the United States.

2. Exchange Agreements

Simulation and modeling play an integral part in the design, integration, and evaluation of most modern weapon systems. Exchange of information contributing to advances will occur through a number of mechanisms. The exchanges in physics and electronics previously noted will contribute directly to our understanding of basic phenomenology at the device level. Empirical validation of environmental models results from exchanges involving the weapons environment.

The Technology Cooperation Program (TTCP) provides mechanisms for a range of applicable exchange activities in such diverse topics as simulation of infrared scenarios, training, simulation of nuclear weapons effects, radar performance prediction, and weapon effectiveness, all of which have traditionally relied heavily upon modeling and simulation.

Each of the Services also has exchanges, primarily with NATO, in areas of specific interest. These provide mechanisms for exchanges of technology such as flight simulation, simulation of air-to-ground sensors, and modeling of flight dynamics.

6. PHOTONICS

6. PHOTONICS

A. DESCRIPTION OF TECHNOLOGY

Photonics is the use of light (photons) for the representation, manipulation, and transmission of information. Photonics technology encompasses techniques to generate photons in highly selective frequencies, wavelengths, and amplitudes (such as in lasers); to guide that light to specific areas (such as through fiber-optic "light-pipes"); to analyze electromagnetic radiation (e.g., by varying frequencies, amplitudes, and polarization); and to develop materials that have desired optical properties (such as reflectance, transparency, and electro-optical properties).

Defense photonics developments are aimed at achieving major improvements in tactical and strategic command, control, communications, and intelligence (C3I) capabilities through faster, smaller, more reliable, and more survivable systems. DoD advanced technology developments in photonics include fiber-optic communication, optical signal processing, optical computer networks, optical memories, nonlinear optical processing, integrated optoelectronic networks, and integration of electronic and photonic devices into monolithic compound semiconductor optoelectronic integrated circuits (OEIC).

Photonics technology has long been used in important niches in both defense and commercial applications. But it has been only recently (the last 10 to 20 years) that photonics technology developed the necessary critical mass of tools and capabilities to springboard into revolutionary new applications.

Today, photonics technology can support a number of applications that previously were the sole realm of electronic and microelectronic devices. By combining fast, massively parallel techniques with devices possessing high spatial resolution (as used in optical data storage), photonics can provide order-of-magnitude improvements over today's conventional electronic devices.

Photonics, like electronics, is an enabling technology which has applications across a number of the critical technologies. Some of these photonic applications are addressed in other sections of this plan (e.g., passive sensors, sensitive radar).

Technology Sets in Photonics

- Laser devices
- Fiber-optics data
- Optical signal processing
- Integrated optics

During the past decade, fiber optics has greatly matured as it has gained importance in the commercial sector. The next decade will see similar maturation of fiber optics for use in the defense sector. Fiber optics will provide higher bandwidth capabilities at lower cost than cable by factors of 10 to 100. The small size, light weight and resistance to electromagnetic interference of optical fibers provide major advantages for deployment in avionics, microwave systems and communication systems. Supercomputers and high-throughput signal processors will use optical interconnects. Ultra low-loss fluoride fibers with their theoretical loss of 10^{-3} db/km will permit transoceanic repeaterless links that could revolutionize undersea surveillance, long distance communications, and tethered vehicle command and control, such as fiber guided missiles. Fiber-optic sensors will provide a new class of gyros for inertial navigation as well as acoustic and magnetic sensors for anti-submarine warfare (ASW) and commercial applications.

The next 20 years will see the emergence of photonic signal processing devices in sensor, communication, and information processing systems. The processing rates required by emerging electro-optical and infrared (IR) sensors, electronic warfare, and undersea surveillance are surpassing the capabilities of currently available electronic processing (1^{10} Gbit/sec). Dedicated photonic processors will soon be needed to act as sensor front ends that will preprocess the data and reduce the data rates to those compatible with current and projected electronic processors. Dedicated special-purpose photonic processors are now in use with DoD in such front-end applications. Defense photonic developments are aimed at achieving major improvements in tactical and strategic command, control, communications, and intelligence (C^3I) capabilities through faster, smaller, more reliable, and more survivable systems and in sensor applications for target detection and weapon guidance.

Laser diode arrays are being developed to scale up the usable light output from diode lasers while retaining the high efficiency (greater than 30 percent) and compactness (approximately 100 micrometer dimensions) of individual devices. For commercial applications, diode arrays may replace other less efficient, reliable, and compact types of lasers.

The evolution of integrated optics occurred in parallel with lasers, fiber optics, and integrated electronic circuits. This evolution will likely continue over the next 20 years. Although currently limited by materials availability, integrated optics will have a similar impact on photonic systems as microelectronics technology had on the electronics industry. These impacts include decreased size and weight of photonic and hybrid photonic/electronic systems and increased speed and reliability.

B. PAYOFF

1. Impact on Future Weapon Systems

a. Weapon System Performance

The table below outlines the goals and payoffs associated with the DoD program in photonics:

Goals and Payoffs — Photonics

Application	Goal	Payoff
Electronic Warfare	• 100X increase in processing rate • 10X fewer physical hook-ups • Distributed architecture • Reduced EMI susceptibility	• Greatly improved ECCM capability for all types of sensors (IR, radar, EW, acoustic, etc.) • Enable processing of data from high density (> 10^6 element) focal plane arrays, very large phased arrays, and collection systems
Command, Control, and Communications (C^3I)	• Transoceanic repeaterless cabling • Satellite-to-submarine communication • Fly-by-light • Satellite-to-satellite crosslinks	• Large distributed ASW systems with lower costs and higher reliability • Improved tactical and strategic connectivity • Reduced weight/volume and lower EMI/ECM susceptibility

The superiority of fiber optics over copper-based systems can be measured by information carrying capacity (which is 10,000 times greater for optical systems), energy loss in signal transmission (100 times lower), error rate (10 times lower), greatly reduced size and weight, and by its resistance to electromagnetic interference, and other harsh environments. Future developments in semiconductor lasers promise improvements in diode-pumped lasers as well as fast, efficient, high-brightness sources for memory, display, and materials processing technologies. Modulators promise still greater improvements in data rate capacity and link margin.

Ultra low-loss fiber optics is of particular importance to DoD in a number of critical military capabilities:

- Wide-area communications
- Wide-area surveillance
- Undersea and tactical missile guidance (low-cost, target and aimpoint selection)
- Remote surveillance and tele-operated weapon platforms (removing the requirement for personnel to enter high-threat areas).

Developing technologies such as zirconium fluoride (ZrF) glasses will enable such systems as large aperture, high-gain, acoustic arrays (thousands of acoustic sensors interconnected over tens of kilometers), and long-range command-guided anti-ship missiles. Important elements of this technology are continuous integration of electronic processors and controllers with fiber-optical devices; nuclear hardening; improved interconnects; switches and multiplexers; higher power; frequency tunable optical sources; and high bandwidth sensitive detectors.

Photonic processing, both analog as well as optics in digital computer systems, offers the promise of order-of-magnitude improvements in processing speed resulting from the natural parallel architecture and the high switching speeds of optical devices. In addition, photonic circuits eliminate many potentially troublesome connectors and increase reliability. The processing rates required by emerging electro-optical and infrared (IR) sensors, electronic warfare, and undersea surveillance are surpassing the capabilities of currently available electronic processing and communication link capability (1^{-10} Gbit/sec).

Photonic devices also offer superior electromagnetic pulse (EMP) and radiation hardness. Developing photonics technologies applied to advanced nuclear weapons testing diagnostics are providing new insights into weapons physics that will enable more reliable, safe, and innovative nuclear weapons development that will be especially critical in the present constrained environment for nuclear testing.

Incoherent diode laser arrays operating in a long-pulse mode are finding use as pump sources for neodymium and other rare earth solid-state lasers. In this application, their ruggedness, reliability, and energy efficiency greatly exceed that of conventional flashlamp pump sources. Diode-pumped solid-state lasers have demonstrated 10 times higher efficiency and 100 times better reliability than flashlamp-pumped laser systems. These sources at primary laser wavelengths or frequency converted shorter wavelengths may enable simple, rugged systems for optical communications, chemical detection, and clear air turbulence detection. This same technology applies to many medical and industrial uses. Incoherent arrays are also being used for direct optical ignition of pyrotechnics (e.g., explosive bolts on rockets) through optical fibers. These lasers require modest (1 watt) power levels and are expected to be a high-volume application because they significantly enhance safety and EMP resistance. Other applications for ignition of energetic materials in conventional and nuclear weapons are likely to follow.

Coherent diode laser arrays have application in satellite communications, directed energy, and undersea ASW. In-phase operation of an array directly increases the amount of power that can be focused on target. In addition, by controlling the optical phase of each of the emitting diodes, electronic beam steering has been demonstrated at very low power levels.

Nonlinear optical materials have important applications in optical countermeasures, and blue-green submarine laser communications.

Integrated optics has the potential to enhance weapon capabilities in the areas of automatic target recognition, state-of-health monitoring, and detection avoidance. Similar to the improved capabilities of electronics with the introduction of the integrated circuit, integrated optics will yield systems which are stable in alignment, allow easy control of guided waves, are electromagnetically immune, have fast speed of operation, and are compact and lightweight. The long term advantage is that the integration could permit mass production and thus reduce costs per unit for assembly.

b. Weapon Systems Logistics

The increased storage capacity, speed, and processing power of photonics technologies will place substantial demands on DoD's capability to find and isolate faults due to the massive amounts of information being processed. Therefore, in conjunction with the technology development, new data checking algorithms and data processing architectures that address operational support and maintenance concerns must be developed.

Once developed and standardized over a broad spectrum of applications, photonics will support diagnostics needs with new passive optical sensors, status monitoring devices, and new inspection techniques.

New fiber-optics applications will provide one to two orders of magnitude greater information bandwidth. This capability coupled with new high density storage of technical information (using CD ROM and WORM) will make practical portable automated technical manuals and highly accurate portable automatic test equipment. This technology also will permit the rapid update of technical information needed to maintain complex weapon systems.

Photonics technology advances will also help eliminate two very troublesome sources of logistics maintenance problems: electrical connections and electromagnetic interference (EMI). New fiber-optic and laser diode connections will reduce classic problem sources such as electrical shorts, opens, and corroded connectors. Since fiber optics are not influenced by spurious electrical inputs, great numbers of primary EMI sources, wires that act like antennas, will be reduced.

The reliability and survivability of future weapon systems using photonics technology will depend upon the susceptibility of those systems to potential threats. While research to date shows photonic systems have an inherent resistance to EMI, continued research needs to be conducted to assess the potential impacts of radiation threats on optical signal/data processing and integrated optical components.

2. Potential Benefits to Industrial Base

a. Manufacturing Infrastructure

Key manufacturing facilities for photonic technologies are still in development. The supporting industrial base is loosely structured, with significant changes anticipated to support the variety of expected applications. Photonics R&D should significantly affect the high-speed computing industrial base through the development of components such as high-speed lasers, detectors, sensors, interconnect media, and signal routing and control elements. DoD relies heavily on commercial development in areas such as high-speed local area networks (LANs) and transoceanic cabling. Fiber optics R&D being pursued by DoD is highly specialized (e.g., intrusion resistant fiber optic links).

Diode laser arrays are expected to have numerous industrial applications, replacing older types of laser due to the greater reliability and lower cost (inexpensive enough to warrant replacement rather than repair). Applications include laser printers, read/write optical disks, and illumination for robot vision. In manufacturing, diode arrays are expected to find widespread use in applications requiring power levels of 1 to 100 watts. These include machining (cutting, drilling) and surface-treating (conditioning, texturing, heat-treating) of a variety of materials. The small size and relaxed power and cooling requirements of diode arrays allow direct point-of-use positioning, eliminating the need for beam transmission optics.

b. Logistics Infrastructure

Photonics will support future needs to pass data across product and support levels. New integration and analyses of maintenance information will be practical due to the higher speeds and processing power. Opportunities to feed back system maintenance and performance data in time to influence product design and/or support decisions will be made practical. Photonics will be an enabling technology for linking many new CALS information exchange and interchange applications.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

The defense-related development plan for photonics focuses upon those key issues that provide substantial, perhaps revolutionary, capabilities related to the national security. The following describes efforts in each technology set.

a. Laser Device Technology

(1) Objective

To develop tunable diode laser devices and arrays with outputs of 100@ or greater, Continuous Wave (CW) coherent power. Continue research in laser, electro-optical, and non-linear optical materials including growth, fabrication and evaluation in order to improve materials and establish low cost manufacturing.

(2) Development Milestones

- FY 1991, 2.5 KW/cm2 peak monolithic diode array.
- FY 1992, 1W CW, single frequency, diode device with diffraction-limited, collimated output
- FY 1993 50W visible-wavelength diode arrays developed. Demonstrate 5W diffraction-limited, single frequency device
- FY 1994, develop 200 Hertz/500 milli-Joule green-blue laser device. Demonstrate tunable frequency conversion in mid-IR band
- FY 1996, demonstrate doubled diode at 1 Joule in blue band, develop high power solid state tunable laser source.
- FY 1997, demonstrate IR countermeasures brassboard. Demonstrate 50W diffraction-limited output from a semiconductor laser system.

b. Fiber Optics

(1) Objectives

To increase gyro accuracy, increase local area networks signal throughput, demonstrate fiber-optic sensor in acoustic applications, and obtain high bandwidth capability.

(2) Development Milestones

- FY 1992, demonstrate 100 GHz fiber optic waveguide modulator.
- FY 1995, demonstrate ultra low loss single mode fiber (< 0.01 db/km loss).
- FY 1996, demonstrate high strength fiber optics fiber (0.5 m with 300 kpsi).

c. Optical Signal/Data Processing Technology

(1) Objective

To obtain orders–of–magnitude improvement in signal processing speed as a result of high speed optical devices.

(2) Development Milestones

- FY 1993 demonstrate phase–only correlator.
- FY 1997demonstrate optically–driven 10^6–pixel spatial light modulator.

d. Integrated Optics Technology

(1) Objective

To provide high–speed, reliable interfaces between electronic and photonic components.

(2) Development Milestones

- FY 1992, gradient index optics demonstration.
- FY 1993, holographic optics demonstration.
- FY 1994, monolithic integrated optical preamp.
- FY 1995, binary optics demonstration.

2. Technology Objectives

Technology Objectives — Photonics

Technical Area	By 1996	By 2001	By 2006
Secure Communications	• Limited-intrusion detection without encryption to 50 MBPS • 2 Gbit/sec Local Area Network (LAN) • 20 GHz bandwidth undersea cable demonstration	• Secure optical systems communications without encryption • 5 Gbit/sec LAN • 10 GHz bandwidth undersea cable	• 10 Gbit/sec LAN
Optical Information/ Processing	• 10x improvement in spatial light modulators and dynamic range • 14-inch tactical optical disk with 6-GB data capability • 10^3GB read-write-erase optical disk – 1.6 gbps throughout • 500 MOPS signal processing • 200 MHz ELINT recorder/processor • Optical interconnect for computer • Optical correlation and modulator	• 14-inch jukebox tactical optical disk with 120-GB data capability • 1 GOPS signal processing • High accuracy/high density light-weight phased array atennas • 1 GHz ELINT recorder/processor • Medium density/high accuracy L-, S-, and X-band optically controlled phased arrays	• On-chip, massive optical interconnects • Opto-electronic heterodyne receiver for laser radar • 10^5 neuron optical neural network
Laser Device Technology	• 10x reduction in cost of diodes and arrays (coherent, area)	• 100W, CW, coherent laser array • 1-D and 2-D arrays with low threshold (<1 ma) and high differential quantum efficiency	• Fully coherent and individually addressable 2-D arrays for beam steering
Integrated Optics	• Gradient index optics • Holographic optics • Binary optics • Monolithic integrated optical preamp	• Integrated photonic/electronic/ microwave devices	• Integrated optical signal processor for spectrum analysis • Fully integrated opto-electronic signal proprocessing capability (digital and analog)
Solid State Lasers	• Diode-pumped 1-KW diffraction limited laser	• Diode-pumped 10KW diffraction limited laser	• Diode-pumped 10KW diffraction limited laser with wavelength diversity

3. Resources

S&T funding[6] for this critical technology is shown below.

Funding – Photonics ($M)

FY87–91	FY92	FY93	FY94	FY95	FY96	FY97
710	186	190	180	179	190	173

4. Utilizing the Technology

A number of other ongoing DoD activities are related to exploiting photonics technology. The Navy is pursuing a diode-laser/solid-state laser approach to underwater applications including submarine laser communications, tactical airborne laser communications, and mine detection and bathymetry. The Air Force is sponsoring work on lasercom satellite-satellite crosslinks which will be able to operate at high data rates and will be smaller than their RF alternatives. In addition, DoD is developing diode-pumped lasers for jamming and/or damaging sensors.

All of these applications require higher laser power and/or efficiency than is currently available. The three- to fourfold increase in each parameter with laser diode pumping directly results in increased performance but with a lower expected maintenance burden. Much of the technological infrastructure for field deployment of diode-pumped solid state lasers such as power supplies, coolers, and coupling optics is being developed on these programs.

DoE efforts are underway to use laser diode arrays for high-power trigger signal generation, power transmission via an all-optical interface, optical switching of high-power electrical pulses, direct optical detonation, range and imaging laser radar systems, and optical correlation. Further, advanced optical guided-wave electro-optic devices, very stable laser sources, and advances in multi-channel optical detectors (streak cameras) are enabling the development of sophisticated high-bandwidth, high-fidelity, real-time analog data links for instrumentation in the nuclear test environment.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

U.S. manufacturing capabilities in photonics can best be assessed by considering the following three application areas.

a. Fiber Optics

The $100 billion annual market in photonics is primarily in commercial applications, and the key product in this area is fiber-optic cable. While U.S. industry is meeting market demands, current manufactured products do not meet all of the DoD requirements for

6 Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgement how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity

ruggedness over temperature range and higher performance (bandwidth, loss). Currently DoD–unique manufacturing technology programs are developing production processes for fiber optic technology applications to secure telecommunications and tethered missiles, torpedoes, and ground vehicles.

Fiber optic sensors are the major commercial product in this area, and the current market is about $5 billion annually. Component quality and reliability (i.e., super luminescent diodes/laser diodes) are currently provided by foreign sources. They require long lead times and are very costly. Extensive commercial R&D is underway.

b. Optical Signal/Data Processing

Approximately half of the demand for photonics in information processing is for commercial applications. Optics technology is utilized in digital input/output inter–connections.

The information storage market is still dominated by magnetic disc storage. However, present manufacturing capability for optical standard discs is 5.25 inches, one of three types of optical discs currently being manufactured (others are erasable optical and write once read many times (WORM)). U.S. industry trails Japanese in cost and quality of current manufactured optical discs. Overall growth rates of more than 15 percent per year are predicted in the optical storage and display industry during the next 5 years.

c. Integrated Optics

Although the science and technology of integrated optics is over two decades old, there are few devices on the market or embedded in commercially available systems. Integrated optical packaging of a number of monolithic optical devices has been demonstrated. In addition, many different materials have been used including glasses, photoresist, polyurethane, sputtered dielectrics, and single crystals. The most commonly used materials are semiconductor gallium arsenide, and the electro–optical crystal (titanium doped) lithium niobate. The latter is popular as a result of its large electro–optic effect whereas gallium arsenide may also be used to fabricate transistors, photodetectors, and other microelectronic devices, thus providing a bridge between integrated optics and integrated electronics.

2. Projected Industrial Capabilities

The U.S. industrial base generally is not expanding its technology emphasis because of limited market demand. However, lasers (laser jamming systems, etc.), optical gyros (several companies are testing preproduction fiber gyros), fiber optic connections, and newer approaches to information processing should receive manufacturing technology funding to address producibility issues. Ultra low–loss fiber optics will require new manufacturing processes to remove impurities. Other contemporary DoD manufacturing technology investments supporting and utilizing this critical technology are aimed at reducing the costs of fiber–optically controlled missile components. In addition, though not considered a true part of photonics, the DoD has an optics thrust program and has established a new Center for Optics Manufacturing to develop new manufacturing capabilities for certain types of optical glass and improve the domestic competitiveness of the optics industry. SDIO has also funded a survivable optics manufacturing development and integration (to develop advanced optics production capabilities).

The manufacture of high-power diode arrays is a very specialized technology due to critical requirements for device growth, processing, and mounting. These devices are fabricated from gallium arsenide (GaAs), and little specialized equipment for volume processing is currently available. In addition, the fabrication of diode lasers requires mirror fabrication equipment. Current technology for the fabrication of diode arrays is labor intensive, but efforts are underway to reduce unit cost for incoherent arrays through volume production and standardization.

The use of some solid state laser materials is impeded by the lack of high quality crystal growth in industry. Nd:YAG crystals are limited in useful diameter to about 2.5 cm; other crystals are not readily available. Certain non-linear materials are in short supply; LiB_3O_5 is obtained from China, $ZnGeP_2$ is currently available only in the USSR.

The development of advanced optoelectronic integrated circuits will require significant strengthening of this country's industrial base in compound semiconductor manufacturing. Only a limited number of commercial companies are capable of manufacturing devices.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

A number of government agencies besides DoD support R&D in photonics. DoE has contributed in several areas: computer modeling of laser diode array devices and cooling. Extensive numerical codes are now available to perform predictive modeling on both surface and edge emitting laser diode arrays. These codes provide a powerful research tool for testing new concepts and designs prior to experimental implementation. DoE's laser program has also focused on issues of heat removal and on providing innovative designs for mounting high power laser devices for optical pumping of solid state lasers. These designs are targeted toward fusion and isotope separation programs. Visible upconversion lasers suitable for diode pumping with outputs at high frequency have been demonstrated.

Diode array development in the national laboratories is concentrated on the development and qualification of arrays for weapon applications plus fundamental research aimed at understanding the coupling and phasing of the individual diodes in an array. This work has also included the development of edge and surface emitting coherent arrays with advanced features such as on-chip injection locking for control and beam steering. Pioneering work in strained quantum-well lasers offers lower thresholds, greater bandwidth, and a wider choice of lasing wavelengths for excitation of efficient fiber-optic amplifiers.

NASA has R&D programs in optical communications, optoelectronic integrated circuits, optical correlation for automatic object recognition, and solid-state lasers for lidar applications. The research programs in solid-state lasers are conducted at the NASA Langley Research Center and the Goddard Space Flight Center (GSFC). Optoelectronic technology development is done at the Jet Propulsion Laboratory using state-of-the-art facilities in microelectronics fabrication in the Micro Devices Laboratory. Optical communications research is carried out at JPL and GSFC. Advanced research in optical correlation for pattern recognition in almost any orientation is carried out at the Ames Research Center.

NIST has several optoelectronics programs: developing a measurements and standards base to support optical telecommunications, encompassing the characteristics of optical fibers, integrated optical waveguide devices, sources, modulators, and detectors; providing standards and measurement services for radiometry; researching optical materials;

developing optical sensors; developing ultra-stable lasers and their application to spectroscopy; and developing optical frequency standards.

NSF supports research on optical materials; optic and electro-optic devices; and optical systems synthesis. Support is provided through ongoing programs in materials research, physics, computer and information sciences, and engineering. In addition, NSF funds two centers with research related to photonics. The Optoelectronic Computing Systems Center focuses on expansion of the intellectual foundations of optoelectronic systems and devices, and on the discovery and demonstration of new knowledge using proof-of-principle machines. The Center for Telecommunications Research includes a research thrust on fundamentals of lightwave devices.

2. R&D in the Private Sector

Extensive domestic industrial R&D efforts in photonics technology are underway, particularly in the telecommunications industry. Fiber-optics are essential to the telecommunications industry, and fiber sensors are being employed in medical, process control, and safety monitoring applications, to name a few.

US research in single mode fiber-optic systems is driven by an ever increasing demand for bandwidth. For example, in high-definition television, even with data compression, data transfer rates of 135 Mb/sec may be needed. A number of experimental projects are underway to introduce fiber optics to provide commercial information and television service to homes. One of these will provide the initial test of microwave frequency (2 Gb/s) subcarrier multiplexing.

Because of the potential for space-based lasers with these approaches or with the closely related diode-pumped solid-state laser approaches, a number of defense companies are sponsoring IR&D projects in diode lasers, which complement the government investments.

Several universities have established consortia with industry and/or government partners to pursue work in optical computing, including the Optical Circuitry Cooperative at the University of Arizona's Optical Sciences Center, the University of Southern California's National Center for Integrated Photonics Technology, the University of Alabama at Huntsville's Center for Applied Optics, and the Center for Optoelectronic Computing Systems at the University of Colorado. Several universities, notably the University of Illinois and the University of New Mexico, have made excellent progress in high efficiency, quantum well laser devices. In addition, a number of universities have excellent programs in optoelectronics including the fabrication and study of 1-D diode arrays. These include California Institute of Technology, University of Illinois, University of California at Santa Barbara, University of New Mexico, Cornell University, and the University of North Carolina.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Ultra low-loss (less than 0.01 db/km) fibers
- Research in bistable devices and other specific components

- Increased volume production of high-power laser diode arrays
- Development of optical interconnects, including fiber-optic backplanes
- Greater than 2 Gbit/sec local area networks
- Radiation-hardened components
- Application of fiber-optics to improved inertial sensors.

The table on the following page provides a summary comparison of U.S. and other nations for selected key aspects of the technology. The United States and Japan share a worldwide lead in this technology. NATO allies have significant efforts that, in aggregate, have the potential to rival either the United States or Japan. The commercial and military potential of photonics is such that most of the industrialized countries of the world are making a significant national commitment to develop photonics.

a. General

Principal cooperative opportunities continue to exist with the European countries and Japan, especially in applications of compound semiconductor superlattices and organic nonlinear optical materials. Cooperative opportunities also exist with many of these countries in niche technologies relating to associated components required to fully exploit low-loss fiber capabilities and to exploit fiber optics technology in harsh environments.

NATO activity involves government, industry, and universities. The combined Euromarket planned for 1992 is expected to promote the integration of current effects in Europe on photonics, including advanced optoelectronic technology, quantum wells and superlattices, materials, focal plane arrays, optical interconnection, and switching, as well as on the application of these technologies to remote sensing, imaging, and industrial processes. France's previous dominance in the area of photonics will be shared with the UK, Germany, and Sweden.

Other countries with significant development efforts in photonics include Switzerland, the Netherlands, Israel, China, Singapore, and Korea.

b. Fiber Optics

Japan leads the world in transferring R&D in fiber optic technologies to various commercial applications and has manufactured considerable amounts of low-loss fiber optics and the ancillary photonic devices needed to use them effectively. Researchers at Konica Corporation have developed a phenol derivative material which can convert low frequency infrared laser light into high-frequency visible light; one projected application is used in fiber optics. Keio University has created graded-index optical fibers of methyl methacrylate-vinyl benzoate copolymer which have low loss and high bandwidth. The UK, France, and Germany also have technically advanced efforts in fiber optics. These countries can all produce low-loss optical fibers but may have difficulty in producing the fibers in large quantities.

Development of high-speed optical interconnects is vital to reducing bottlenecks in fiber optic communication systems and to constructing viable optical computers. Siemens AG in Germany is studying laser diodes with single-mode fiber couplers. The Australian National University is investigating transmission characteristics of a nonlinear coherent couple composed of anisotropic fibers. A fiber optic community newsletter announced that a

Summary Comparison — Photonics

Selected Elements	USSR	NATO Allies	Japan	Others
Ultra low-loss (less than 0.01 db/km) fibers	□□	□□	□□□ +	□ Various
Development of optical inter-connects, including fiber optic backplanes	□	□□	□□□ ○	□ Brazil
Greater than 2 Gbit/sec LAN	□	□□□ ○	□□□□ +	
Application of fiber optics to improved inertial sensors	□□	□□	□□	
Research in photonics, bi-stable devices, other specific components	□□ [a]	□□□ ○	□□□ ○	□□□ ○ Israel, China
Radiation-hardened components	□□	□□	□□	
Increased volume production of high-power laser diode arrays	□□	□□□ ○	□□□□ +	
Overall[b]	□□	□□	□□□□ +	□ Various

[a] The Soviets are reported to have a world lead in spatial light modulation.
[b] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□	broad technical achievement; allies capable of major contributions
□□□	moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
□□	generally lagging; allies may be capable of contributing in selected areas
□	lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

+	Foreign capability increasing at a <u>faster</u> rate than the United States
○	Foreign capability increasing at a <u>similar</u> rate to the United States
—	Foreign capability increasing at a <u>slower</u> rate than the United States

manufacturing firm in the UK has discussed development of rugged environment fiber-optic connectors.

c. Laser Diodes and Arrays

The United States has a lead in the area of laser diode array technology. An example of this lead is Xerox Palo Alto Research Center's multiple-wavelength diode laser superarray demonstrated in April 1990. Varian announced in August that it has developed a GaAs semiconductor power receiver which converts light from a laser diode transmitted via fiber optic cable into electrical power. Use of narrow linewidth diode lasers and tunable solid-state laser sources has allowed U.S. researchers to optimize solid-state laser compositions for diode pumping. The Soviet Union lags in this area, largely due to the lack of vapor phase growth technology, which is essential for obtaining high quality material for the fabrication of low-threshold, high-efficiency laser diode arrays. The Soviet Union also trails the United States in the modeling of arrays. A recent Soviet study published in Radiotekhnika concerns the effect of power supply on the radio-frequency noise spectra of laser diodes.

Furukawa Electric Company, Ltd. has been researching facet coating of laser diodes and has announced the reduction of threshold current and enhancement of characteristic temperature in GaInAsP multiple-quantum-well laser diodes. NEC Corporation has performed experiments on spectral linewidth in multiple-quantum-well distributed feedback laser diodes. NEC has also demonstrated a photonic wavelength division switching system using tunable laser diode filters.

France, the UK, Germany, and Sweden all are actively researching laser diodes and they (and Switzerland) are active in the field of quantum wells and superlattices for optical and integrated optical devices. For example, scientists at the University of Southampton in the UK have worked with sequential power transfer between stripes of a diode laser array through photorefractive two-wave mixing in $BaTiO^3$. Siemens AG has been performing yield analyses of distributed-feedback, metal-clad, ridge waveguide laser diodes for coherent system applications. CNET is a leading French laboratory working with laser diodes; one recent study was the calculation of antireflection coatings on semiconductor laser diode optical amplifiers.

The People's Republic of China also has fostered scientific work in laser diodes and quantum wells. Jilin University has fabricated a new type of surface emitting semiconductor laser diode. Hangzhou Institute of Electronic Engineering has demonstrated the bistability of a bistable laser diode integrated monolithically with a photodetector.* The PRC is also pioneering development of novel, non-linear optical materials.

d. High-Speed Networks with Fiber Optic Backplane

A number of companies, including AT&T, Rockwell, other U.S. companies, and Japan's NEC, have announced plans to market synchronous optical networks. One U.S. company, Photonics Corporation, is currently marketing a local area network with a different photonic approach -- the connection is through IR emitters and sensors rather than through fiber-optic cable.

e. High-Speed, Low-Energy Optical Switches

The U.S. is well on the way to commercial production of photonic switching technology. AT&T announced optical switching marketing plans with a (maximum) 5 year goal. However, AT&T faces stiff competition in the field from Japan and Germany. In March 1990, Japanese researchers at NTT Transmission Systems Laboratories announced the development of all–optical ultrafast nonlinear switching using the Kerr effect in optical fibers. At the same time, scientists at Hitachi Ltd. announced an INP–based optical switch module operating through carrier–induced refractive index change which is to contribute to the development of practical optical switch arrays. In April, NTT proposed an oblique–polishing tilted–coupling method for suppression of feedback light in laser diodes and waveguides. In May 1990, NTT reported the achievement of an ultrafast, lowpower, highly stable all–optical switch in a non–linear Sagnac interferometer. The Phys.– Tech. Bundesanstalt in Germany has announced findings in bistability and optical switching of spatial patterns in a helium–neon laser oscillating in the TEM01 hybrid optical resonator mode. France, the UK, Denmark and Sweden also have much active research in bistable and high–speed optical switching. Heriot–Watt University in Edinburgh has researched the effect of pixelation on the switching speeds of InSb bistable elements. Pixelation may reduce cross talk or power requirements in optically bistable devices. Odense University in Denmark has performed studies of high–speed optical switching in CdSe. The USSR is also actively pursuing this technology area. The Academy of Sciences of the USSR published a study on spatial restructuring of the character of optical switching in a bistable semiconductor interferometer. Kalinin Polytechnic Institute scientists researched the dynamics of switching processed in bistable systems with delayed feedback.

f. High–Performance Spatial Light Modulators

The United States has been working on developing high–performance spatial light modulators for several years. Lockheed is attempting to develop a spatial light modulator for use in an optical computer. Thomson–CSF in France has developed a low–loss and low–drive–voltage electro–optical phase modulator at 1–.6 micrometers. British Telecom has worked on a two–dimensional array of InGaAs/InP multiple–quantum–well modulators. Academia Sinica in the PRC has presented a study on GaAs/GaA1As single quantum well electrosorption and light modulation.

Although the DCTP interest in this field is in the development of more sophisticated spatial light modulators, a number of scientists have been experimenting with applications of spatial light modulators in other areas of photonics. AT&T believes that spatial light modulators hold the key to advances in optical computers and photonic switches. Japan (University of Tokyo and Hamamatsu Photonics) uses spatial light modulators for learning capabilities in optical associative memory devices. The TechnionIsrael Institute of Technology is using spatial light modulator technology and iterative learning procedures to generate holograms.

g. Optical Signal/Data Processing

Japan is pursuing research and development in all areas of optical processing, with government, industry, and universities all heavily involved. The key government participant is the Ministry of International Trade and Industry (MITI). Most of the large electronics companies in Japan have made a commitment to this effort. A special trade organization, the Opto–Electronic Industry and Technology Development Association, was founded in 1980 to coordinate industrial activity, foster cooperation, and encourage standardization. Universities in Japan are performing much of the basic materials research on which the technology development is so dependent. In 1984, the Japan Society of Applied Physics established a research body called the Optical Computer Group, which illustrates how seriously Japan is taking the field of optical computing. The group has members from universities, government laboratories, and private companies.

Basic research is being carried out in France, the UK, Germany, and Sweden with complex GaAs/GaAlAs and InGaAs/P structures. Singapore has named laser technology and electro-optics as one of its areas of interest for a high-technology R&D push.

h. Integrated Optics

The United States is the leading research presence in integrated optics, in part due to the efforts by AT&T and other communications concerns. The other major performers are the United Kingdom, Japan, and Western Europe. There are indications that future Japanese effort may be increasing if not already accelerated.

i. Radiation/Environment Hardened Photonic Devices

A number of U.S. government laboratories including the U.S. Air Force Weapons Laboratory and the U.S. Naval Research Laboratory are researching and measuring radiation-induced attenuation in optical fibers. This may lead to methods of counteracting the radiation effects. Varian announced that its manufacturing technique for the GaAs semiconductor (optical) power receiver can be mass produced and used for sensors in nuclear weapons testing and harsh chemical environments. As noted in a UK fiber optic community newsletter, one manufacturer in the UK is interested in developing a rugged fiber optic connector. The Technical University of Lublin in Poland is working on the problem of fatigue in optical fibers working in dynamic robotic systems.

j. Optical Sensors

Although there is interest in rugged photonic devices, the British (University of Southampton, University of Strathclyde, Pirelli Gen. Plc.) are interested in very sensitive photonic devices as well. They hope to develop fiber-optic sensors sensitive enough to measure minute amounts of breakage, temperature, pressure, magnetic fields, vibrations, and chemical composition. The Japanese Institute of Industrial Science has developed an optical sensor for determination and monitoring of gas components at temperatures of more than 1000°C. The French have developed a fiber-optic current sensor using the Faraday magneto-optic effect in a monomode fiber. Canada's Ecole Polytechnique de Montreal has experimented with nematic liquid crystal clad tapered fiber optic temperature sensors. Italy's research in fiber optic sensors includes an optical sensor for the control of high power laser welding. The Huazhong University of Science and Technology in the PRC is working on signal processing of a fiber optic current sensor. The Academy of Sciences of Uzbek SSR in the USSR is concerned with fiber-optic interferometer temperature sensors.

k. Optical Computing

One of the largest optical computing programs in Europe, the European Joint Optical Bistability Project, involves eight universities and institutes in the UK, Belgium, Germany, Italy, and France. In France, research is being conducted on liquid-crystal light components at the University of Paris (Orsay). Thompson-CSF also is pursuing a major effort on optical processing. In West Germany, Erlangen University is investigating parallel logic, optical cross-bar switches, spatial filtering, and logical operations using polarized light. The University of Duisberg has built a very fast optical multiplier and broadcast bus, which will support communications between modules in a computer. The Fraunhofer Institute has developed an optical local area network.

The German company, Siemens, has announced a method of employing ordinary transistors as light detectors in optical computing systems. Because transistors are already part of the chips in computer systems, they report it is much simpler to employ the photodetection properties of the transistors than to use special light detector devices. Use of this method offers a substantial reduction in circuit signal–delay, although it is not well suited to long distance signal transmission.

Japan is pursuing research and development in all areas of optical processing, with government, industry, and universities all heavily involved. A special trade organization, the Opto–electronic Industry and Technology Development Association was founded in 1980 to coordinate industrial activity, foster cooperation, and encourage standardization.

A number of countries are actively pursuing related topics. In 1988, the Japanese (Fujitsu) demonstrated the first broadband optical integrated services digital network (ISDN). NEC has demonstrated an experimental optoelectronic receiver, using reported development of high–mismatch epitaxy of GaAs and InP, capable of 2–GB/second modulation rates. A number of Japanese firms and British Telecom are pursuing coherent communication techniques that are advertised as having near–term potential to extend transmission capabilities to 4–GB/second. If realized, these capabilities would be significant advances. The UK is also researching special fibers (high–birefringence, polarization–preserving) for sensor applications.

2. Exchange Agreements

There is a significant level of exchange activity in all areas of photonics, including integrated optics, optical materials, fiber–optics, and related components. The NATO Defense Research Group (DRG) programs in physics and electronics and optical and IR technologies provide mechanisms for exchange of fundamental scientific information. The Technology Cooperation Program (TTCP) sponsors a group focused on the military application of optical fibers and components. TTCP also provides a mechanism for exchange of information on basic materials and specific applications. Each of the Services also has exchanges, which cover a spectrum of activities ranging from basic research in optical science with France and the UK, application of the technology to optical processing (principally with France), and a program with Germany for specific application of the technology to the integration of main battle tank electrical, electronic, and optronic systems.

7. SENSITIVE RADAR

7. SENSITIVE RADAR

A. DESCRIPTION OF TECHNOLOGY

Continued reduction in target observables will significantly reduce the effective range of existing U.S. surveillance, tracking, target classification, and weapon guidance systems. Radars will continue as a primary sensor since they provide an all-weather capability and do not rely on threat emissions. Sensitive radars (such as wideband radar, synthetic aperture radar, bistatic radar, laser radar, and advanced over-the-horizon (OTH) radar) will be required to handle future advanced low observable threats and to provide needed ECCM capability. Furthermore, the enormous advances in distributed digital computation and signal processing, when integrated with radar technology and not just following it, can enhance our ability to detect, classify, and attack targets.

Increasing radar sensitivity creates some significant technical obstacles. First, increased sensitivity will require development of frequency generators with increased stability, systems with increased processing gain, and receivers and analog-to-digital converters with wider dynamic ranges. Improvements in signal processing are needed to take advantage of enhanced radar sensitivities. Secondly, increased sensitivity makes our systems more vulnerable to enemy exploitation and interference by unwanted objects (e.g., birds) and phenomena. Resistance to electronic countermeasures (ECM) and anti-radiation missiles (ARM) must be improved. Additionally, we must minimize the potential for mutual interference of our own radars and RF devices in the complex battlefield environment. Improvements in spectrum management and antenna directivity are required, along with attention to the interaction of technical requirements and low-level clutter environments.

Technology Sets in Sensitive Radar

- Advanced monostatic radar
- Multistatic radar
- Radars for non-cooperative target recognition and aided/automatic target recognition
- Phased array radar
- Laser radar
- Electronic Counter Counter Measures (ECCM)

The indicated advances in conventional monostatic radar technology are needed to counter the reduced observable threat, although they may not be adequate. Radar cross section is frequency dependent and is often most difficult to suppress at relatively low frequency. Radar using a relatively low frequency will need to use a broad fractional bandwidth to maintain good range resolution and rejection of clutter. A radar using a wider frequency spectrum is more likely to employ the frequency at which the radar return is greatest.

Multistatic radar, where the transmitter and receiver are separated by a significant distance, provide another method to counter low observables. Low radar cross section targets may deflect the radar signal with higher power at multistatic angles than the forward scattered monostatic reflection. Technological issues include coordinating the timing of transmitters and receivers, and maintaining the bistatic angle.

Real-time, positive identification of targets is crucial in today's operations; however, decreasing target observability and increasing battlefield complexity is making target identification more difficult. The enemy's use of countermeasures to avoid identification, and presence of non-radiating (possibly neutral) intruders further compound the target designation problem. Technologies for non-cooperative target recognition (NCTR) and automatic target recognition (ATR) include imaging and target/radar signal interaction, and may require the use of other sensors (e.g., infrared and acoustic).

Phased array radars use an electronically steered array of transmit/receive elements. They are inherently more reliable and flexible than reflector radar systems which scan mechanically. Phased arrays are being deployed today; however, technology to increase power/aperture products, adapt conformal phased arrays to a variety of applications, and reduce weight and volume is needed. Advanced phase arrays can provide needed immunity to jamming and can serve as powerful, flexible communication links to and from sensors and weapons.

Coherent laser radars are optical wavelength analogs of microwave radars. They provide advantages of bandwidth, physical size reduction (e.g., in antennas), and higher resolution. Laser radar will be used for environmental sensing and for target recognition. At the same time, laser radars possess disadvantages that accrue from scattering and absorption characteristics of the shorter wavelengths. These disadvantages result in attenuation of the coherent laser radar beam and the manifestation of undesirable speckle patterns (arising from target roughness and atmospheric turbulence); this speckle is subject to control to some extent, by optimum processing.

B. PAYOFF

1. Impact on Future Weapon Systems

a. Weapon System Performance

Sensitive radar technology is a major factor in providing a technical edge to U.S. forces by enhancing detection, localization, classification, identification, and tracking capabilities. Radar sensor technology, at both RF and laser frequencies, will remain a major factor in future warfare. It is crucial to develop techniques to counter ongoing threat efforts to reduce the observable radar signatures of weapon platforms.

One method to counter the reduced radar cross section threat is to use a lower frequency radar. Radar cross section reductions made through target shaping techniques have less effect on radars operating at lower frequencies. Lower frequency radar signals can also propagate over longer distances than at higher frequencies; they may also provide a significant detection capability beneath foliage; however, low frequency radars provide insufficient tracking accuracy for weapons control.

Multistatic radar also has some potential to counter low observables. Radar cross section reduction methods include shaping techniques to scatter the radar signal at angles other than the forward, monostatic angle. A multistatic receiver under limited geometric conditions could detect the target where a monostatic receiver might not. This separation technique provides the added benefit of passively engaging the target while actively illuminating it, as is the case with the Patriot missile or with simpler "semi-active" systems. In addition, close coordination of two radars can have additional benefit in locating in both coordinates with range accuracy, as opposed to the worse azimuth accuracy of monostatic radar.

NCTR technology will reduce fratricide and the inadvertent killing of noncombatants. ATR is needed for battle management and for smart, beyond-visual-range weapons. Imaging techniques such as synthetic aperture radar (SAR) will be used for detection and identification of camouflaged or foliage-concealed targets. SAR will also be used for air- and space-based imaging of lower altitude and ground-based targets. Inverse synthetic aperture radar (ISAR) will be used for ship classification. Ultra-high range resolution radar (UHRR) will provide a significant aircraft identification capability. Millimeter wave (MMW) radar imaging will be used in air defense and for fire-and-forget missile seekers. Continued development of millimeter wave radar technology is critical for the Army with its array of small diameter smart munitions and precision-guided munitions that impose severe form, fit, function, and cost restraints on the seeker/sensor design and production.

Phased array radars incorporated into airframes, (e.g., RPVs and long-duration aircraft), light satellites, ground vehicles, and ship hulls will reduce radar signatures, making our systems more survivable. Additionally, scan patterns can be randomized to deter countermeasures. In addition, due to the lack of mechanical parts, phased array radars provide increased reliability and flexibility over conventional reflector radars. Phased arrays can instantaneously dwell in a specified direction. A phased array radar scanning a full 360 degree sector can adapt quickly to changing battlefield conditions and concentrate on a specific target or area of high military interest.

Laser radars (Ladar) provide a highly accurate tracking and weapon control capability. They can provide highly accurate aimpoint selection to enhance the lethality of next generation smart weapons. Laser radar can also provide an important NCTR capability through imaging and target/laser beam interaction phenomena. Helicopters can enhance their survivability by using Ladar for obstacle avoidance. Blue-green laser radars will be used for rapid, shallow-water minefield mapping in support of amphibious operations. Laser radars will be used for remote environmental monitoring, including chemical agent or persistent nuclear dust cloud detection.

b. Weapon System Logistics

Modular designs and the multiple active array elements will provide build-in redundancy in new radar systems. As a result, these new radar architectures will result in systems that rarely experience hard or single point failures. Instead, the systems will experience gradual degradation of optimum performance as parts or modules fail.

New diagnostic approaches and capabilities will need to address operational needs of systems which exhibit gradual performance degradation. These new approaches must be developed in advance of system implementation so that the radar architectures may incorporate diagnostic and repair features that are compatible with the new operational maintenance requirements.

Goals and Payoffs — Sensitive Radars

Sensor Type	Goal	Payoff
Advanced Monostatic Radar System Component Technology	• Counter 1,000-fold reduction in threat observability • Increase RF system robustness • Provide surveillance • Allow passive weapon systems to engage threat illuminated by remote source	• Provide capability to detect, track, and engage advanced threats including stealthy cruise missiles and aircraft. • Improve operational performance in severe environments • Improve resistance to countermeasures • Target does not know that it is under attack • Continuous theater MTI to keep track of all vehicles
Multistatic Radar	• Improve resistance to countermeasures • Allow passive weapon systems to engage threat illuminated by remote source • Counter 1000-fold reduction in monostatic radar cross section	• Provide capability to detect, track, and engage advanced threats including stealthy cruise missiles and aircraft • Improve operational performance in severe environments • Improve survivability
Radars for NCTR and ATR (MMW Radar, UHRR, and SAR/ISAR)	• Provide real-time positive hostile identification • Detect and identify camouflaged or foliage-concealed targets • Identify strategic relocatable targets • Discriminate against countermeasures	• Reduce Fratricide • Enable development and employment of smart, beyond-visual-range weapons • Improve battle management capability and employ weapons more effectively
Phased Array Radar	• Active conformal arrays embedded on structures • High power, narrow beam active apertures • Light, small, power efficient radars • Combine transmit, receive, illuminate and communications function	• Provide capability to detect, track, and engage advanced threats including stealthy cruise missiles and aircraft • Improve operational performance in severe environments • Improve survivability and reliability • Reduce own platform radar cross section • Deployment of radars on light satellites, RPVs, etc.
Laser Radar (Ladar and Lidar)	• Accurate target tracking, identification, and weapon guidance • Detect and identify camouflaged or foliage-concealed targets • Rapid minefield mapping • Real-time environmental monitoring	• Provide capability to detect, track, and engage advanced threats including stealthy cruise missiles and aircraft • Improve survivability • Enhance weapon lethality • Improve weather forecasting capabilities • Improve operational performance in severe environments • Provide remote, real-time detection of chemical agents.

2. Potential Benefits to Industrial Base

a. Manufacturing Infrastructure

Radars represent an industrial base in transition. Conventional radars are a well established commodity for military systems, while sensitive radar technologies are still in development and do not constitute a significant present-day market. Both the conventional and sensitive radar markets are primarily driven by DoD; however, the Federal Aviation Administration does provide a cyclical market for radar products and there is a continuing foreign military sales market. Although sensitive radar technology is primarily military, the technologies can be quite useful in selected commercial endeavors. Sensitive radar techniques will be adapted to commercial airspace control, collision avoidance, non-cooperative target identification, problems of clear air turbulence and wind shear, weather forecasting, and possibly to counter narcotics trafficking.

Eye-safe, low-power laser radars are being investigated for a variety of commercial applications, including robotics, automated manufacturing processes, and speed determination (e.g., police radar). As the cost and availability of solid-state and injection laser radars are improved, substantially broader usage is expected and shorter wavelength tunable laser radar possesses enormous potential for environmental monitoring, including remote assessment of compliance. Use of tunable Ti:sapphire laser radar and high-speed chemometric analysis of spectroscopic signatures can also play a major role in the drug war through the remote identification of chemical c uents associated with drug factories and the remote location of marijuana fields by the multispectral analysis of reflectivity and fluorescence signatures.

b. Logistics Infrastructure

Radar designs incorporating modules and small active array elements will permit more field repair capabilities using remove-and-replace actions which will result in infrastructure growth toward two levels of maintenance. These advancements will permit greater systems availability while reducing depot-level workloads.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Advanced Monostatic Radar

Objectives

To develop advanced frequency generators, processing and radiating technology, using increased operating bandwidth, advanced waveforms and signal processing, and more adaptive antenna designs.

(1) Wideband/Ultra-Wideband Radar

Conventional monostatic radar uses a co-located radio frequency transmitter and receiver operating in the microwave/millimeter wave spectral region to detect, classify, and track targets. Monostatic radar is the primary sensor technology used in land, air, naval, and strategic warfare. Improvements in monostatic radar technology will address advanced, low observable threats. Wideband/ultra-wideband radar (where the bandwidth is at least 50 percent of the center frequency) will help counter a reduction in threat radar cross section by addressing the frequency dependent trade-offs inherent in low observable design.

Development Milestones

- FY 1991, Preliminary wideband clutter characterization measurements. Test wideband RF sources.

- FY 1992, Cued/supercued fire control radar demo.
- FY 1993, Advanced radar technology demonstrations.
- FY 1994, Completion of ultra-wideband MTI/SAR technology development.
- FY 1997, Advanced radar waveform test.

(2) Advanced Over-the-Horizon Radar (6–30 MHz)

Advanced Over-the-Horizon (AOTH) radar may prove useful against the strategic low observable threat.

Development Milestones

- FY 1991, Complete concept design studies and preliminary clutter measurements.
- FY 1992, Conduct coherence experiments.
- FY 1995, Conduct AOTH testbed experiments.

(3) Radar System Component Technology

Advances in radar system components (such as traveling wave tubes, MMIC modules, and high power, fast switching electronics) are needed to implement sensitive radar technology improvements.

Development Milestones

- FY 1992, Demonstrate 90 GHz fast wave [illegible]
- FY 1993, Demonstrate 50–100W (peak) [illegible] G[illegible]z pulsed power transistor.

b. Multistatic Radar Objectives

Multistatic radar shows potential in countering [illegible] low observable threat. Coordination of distributed multistatic transmitters and receivers must be addressed. Clutter and multistatic scattering off of the target need further characterization.

(1) Bistatic Guidance and Conformal Arrays

Remote multistatic transmitters will allow missiles and aircraft to passively acquire and destroy illuminated threat systems.

Development Milestones

- FY 1991, Conduct bistatic air-to-air missile guidance test against flyover targets.
- FY 1995, Bistatic airborne conformal array advanced technology demonstration flight test.

(2) Bistatic Imaging Radars

DoD is exploring bistatic imaging for target identification. As with other multistatic radar applications, the receiving units remain covert.

Development Milestones

- FY 1993, Conduct space shuttle experiment of bistatic imaging of surface targets.
- FY 1996, Satellite-based bistatic SAR targeting demonstration using NASA's SIR-C sensor.

(3) Tactical Multistatic Radars

Development efforts in tactical multistatic radars will emphasize ARM resistance, and rapid and accurate target acquisition and tracking capabilities.

Development Milestones

- FY 1993, Demonstrate ARM resistant bistatic transmitter.
- FY 1994, Demonstrate three-dimensional bistatic acquisition and track accuracies for the Advanced Target Acquisition Counterfire System.
- FY 1995, Demonstrate bistatic adjunct for transition to Forward Area Air Defense Masked Target Sensor.

c. Radars for NCTR and ATR

Objective

Non-Cooperative Target Recognition (NCTR) technologies reduce fratricide. These radars identify a target without the need for a cooperative question and answer identification query. Identification is achieved through either imaging or target/radar interaction. Automatic Target Recognition (ATR) radars provide target data needed by weapon system processors for target determination. This information is input, either automatically or through human intervention, to a fire control system or smart weapon.

(1) MMW Radars

MMW radars, operating at 40 GHz or above, provide high resolution and small antenna size. High resolution MMW radar imaging will be used for NCTR and ATR particularly in air defense, land warfare, and smart weapon applications.

Development Milestones

- FY 1992, Demonstrate MMW beam sharpening techniques.
- FY 1993, Begin development of advanced MMW seeker.

(2) UHRR Radar

Ultra High Range Resolution (UHRR) radars emit a short pulse to obtain a range image of the target.

Development Milestones

- FY 1992, Conduct intra-radar aircraft signature fusion experiment using stepped frequency UHRR waveform.
- FY 1993, Conduct automatic Radar Target Identification (ARTI) field demonstration.

(3) SAR/ISAR

A Synthetic Aperture Radar (SAR) is a high range resolution radar on a moving platform. Platform motion is used to synthetically create a large, high resolution antenna aperture. An Inverse Synthetic Aperture Radar (ISAR) applies the same principles as SAR except that target motion is used to synthesize antenna aperture instead of host platform motion. Both SAR and ISAR use high resolution in range and cross range to form target images. SAR with full polarization capability can reduce speckle and aid target detection in small pixels.

Development Milestones

- FY 1991, Ultra wideband SAR concept evaluation.
- FY 1993, Conduct automatic ship classification IS·AR demonstration.
- FY 1994, Conduct ultra wideband SAR testbed demonstration.
- Conduct camouflage/foliage concealed target detection SAR flight tests. (Date is classified)

d. Phased Array Radar

Objective

To apply advanced, solid-state distributed active processing and emitter technology and conformal design to mobile platform radar requirements.

Development Milestones

- FY 1992, Demonstrate 8-inch active array for integrated guidance/fuse radar; complete development of wideband modules for airborne early warning radar array.
- FY 1993, Demonstrate feasibility of active side-looking array.
- FY 1994, Demonstrate ground-based radar and fiber-optic subarray.
- FY 1995, Demonstrate conformal array airborne/RPV radar.
- FY 1996, Conduct special target phased array radar field test (e.g., on an RPV long-duration aircraft or light satellite).

e. Laser Radar

Objective

Laser radars (Ladar) will be used for target detection and tracking, imaging and identification, navigation, and weapon guidance and control. Laser induced detection and ranging (Lidar) will be used for chemical effluent detection and environmental monitoring. Control of the laser beam and wavelength must be improved. A better understanding of laser/target interaction and laser propagation phenomena under various environmental conditions must be gained.

Development Milestones

a. DoD is developing Ladar technology for target detection and identification. Identification can be achieved through either imaging or laser/target interaction.

- FY 1991, Conduct flight test of forward/down-looking Ladar for camouflage/ foliage concealed target detection.
- FY 1993, Demonstrate Ladar for targeting of strategic relocatable targets.
- FY 1994, Demonstrate target spectral/temporal/structural characteristics identification; demonstrate advanced down-looking Ladar.

b. Improved laser beam and wavelength control will provide resistance to countermeasures. DoD is developing tunable laser radars. Module arrays will be used to create laser beams in a manner similar to phased array RF radars.

- FY 1993, Conduct laboratory demonstration of multi-dimensional Ladar.
- FY 1995, Demonstrate rapid non-mechanically steered beam agile Ladar.

c. Laser radar provides increased accuracy for guidance and control.

- FY 1991, Conduct CO^2 laser radar fire control test.
- FY 1991, Assess air-to-air laser radar missile seeker. Demonstrate compact helicopter Ladar for wire and obstacle detection and avoidance.

d. Ladar will be used in coastal and shallow water areas due to the good propagation of blue-green light through water.

- FY 1991, Advanced Mine Detection and Avoidance System (AMDAS) Advanced Technology Demonstration.

e. Lidar is being developed for environmental monitoring including standoff detection of chemical effluents through laser absorption.

- FY 1992, Demonstrate tunable CO_2 Lidar for standoff chemical agent sensing; begin space-based Lidar experiment.
- FY 1993, Demonstrate wind and vibration sensing. Develop new design Lidar for line-of-sight path characterization of turbulence induced effects
- FY 1994, Demonstrate second generation laser doppler wind sensor.

2. Technology Objectives

Technology Objectives — Sensitive Radars

Technical Area	By 1996	By 2001	By 2006
Advanced Monostatic Radar and Related Component Technology)	• Multiband radar concept demonstration • High dynamic range components • Demonstrate environmental platform limiting factors	• Demonstrate performance against reduced observable threat • OTH testbed performance confirmation	• Demonstrate anti-stealth radar concepts
Multistatic Radar	• Multiple diverse illuminator technology • Interference rejection concepts	• Moving platform • Multiple diverse illumination exploitation • Demonstration of interference rejection technology	• Demonstrate anti-stealth radar concepts
Radars for NCTR and ATR, (MMW, UHRR, SAR/ISAR)	• Develop data base and algorithms for NCTR radar • Field demonstration of 2-D imaging radar	• Initiate FSED on NCTR radar • Transition NCTR algorithms to operational user	• Demonstrate anti-stealth radar concepts
Phased Array Radar	• Demonstrate conformal array radar • Array/platform environment determination	• Conformal array sidelobe control • Complex shape conformal array concept validation	• Demonstrate anti-stealth radar concepts
Laser Radar	• Demonstrate laser radar, beam steering • Demonstrate tunable laser radar for chemical and environmental sensing • Demonstrate ladar for obstacle avoidance and target detection	• Demonstrate ladar for NCTR/ATR and brilliant weapons	• Demonstrate compact tactical laser radars

3. **Resources**

Total S&T funding[7] for this critical technology is shown below.

Funding -- Sensitive Radars ($M)

FY87-91	FY 1992	FY 1993	FY 1994	FY 1995	FY 1996	FY 1997
669	196	201	192	188	191	192

4. **Utilizing the Technology**

DoD programs that presently utilize or may (in the near future) utilize emerging sensitive radar technologies include the following:

- Obstacle Avoidance System (OASYS)—The objective is to provide helicopters with a compact, light-weight, wire and obstacle avoidance sensor to prevent accidental strikes, which cause losses of equipment and personnel.
- Air Defense Target IdentificationLaser vibration sensing is one of a number of candidate technologies being investigated as candidate approaches for noncooperative, positive identification of air targets.
- Infrared Lidar for Stand-Off Chemical Agent Sensing. An IR lidar may be effective as a remote sensor for discriminating among chemical agents.
- The Multiple Launch Rocket System Terminal Guidance Warhead (MLRS- TGW) and the RF Hellfire (Longbow) are fire-and-forget millimeter wave radar systems which are not affected by rain, fog, dust, smoke, and other battlefield obscurants. Both of these programs will utilize components/devices developed by the DARPA-sponsored Microwave Millimeter Wave Monolithic Integrated Circuits (MIMIC) program.
- Forward area air defense.
- Advanced counter battery radar.
- Space-based wide area surveillance.
- NATO anti-air warfare system.
- RPV's, long endurance aircraft, and light satellites

[7] Funding is derived from programs in the DoD budget. Most programs involve several technologies. It, therefore, becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

Phased array technology is being transferred into manufacturing, but application in operational systems has been limited. The APQ-164 radar for the B-1B is a phased array with over 100 systems built. Manufacturing capability received a great deal of attention that is currently being used in advanced phased array programs.

Advanced radar sensors currently under development generally employ a phased array antenna. The antenna may be built from a large number of relatively low-power active elements or from a smaller number of high-power radiation sources that provide power to many transmit elements. The former technique employs solid-state transmit/receive (T/R) modules and has been demonstrated in L, S, C, and X-band. L, S, and C-band modules are available but need to be made smaller and lighter for space applications. X-band modules have been designed, evaluated, and fabricated in several programs to date. The ATF program has concentrated on manufacturing and cost reductions and is projecting costs of less than $400 per module in volume production phases of the program.

Two areas of concern exist in the manufacture of phased-array antennas that depend on a few high-power radiation sources: traveling wave tubes (TWTs) and ferrite phase shifters. TWTs have high failure rates and frequently require long lead times to purchase. Some TWTs for use in military systems are now being purchased from Europe. In response to the limited production capacity, DoD has initiated a DPA Title III program to qualify domestic vendors and encourage these suppliers to increase production beyond bench-scale methods. The manufacturing base for ferrite phase shifters is also rather limited. In addition to electronics manufacturing issues, the dimensional tolerances specified for large phased array antennas create a significant manufacturing problem. Finally, there are few facilities to test large phased-array antennas.

2. Projected Industrial Capabilities

A DoD manufacturing technology (MANTECH) project aimed at reducing the cost and increasing the producibility of X-band transmit/receive (T/R) modules for airborne applications is underway. This program addresses all aspects of the manufacturing process, including test, and should make significant reductions in module cost. The DoD has similar programs underway for L and C-band modules. These programs are crucial to the development of the desired $200/module costs of next-generation systems.

DoD has recently awarded MANTECH contracts to investigate the manufacturing cost and producibility of T/R modules. The program entails the design of a module for manufacturability, use of new cost-effective materials, and innovative assembly and test techniques. Emphasis is on statistical process control, modeling and simulation, automation equipment technologies, and factory system integration.

Millimeter-wave technology is sufficiently advanced to allow fabrication of a radar, but additional efforts are required to develop the manufacturing base. Though laser radars must still be classified as R&D systems, MANTECH programs are being planned and technology applications are ready for transition to a manufacturing environment.

The MANTECH 94 GHz Millimeter Wave Transceiver program provides the first step insertion vehicle for the maturing MIMIC technology as MLRS-TGW transitions from research and development to full-scale production. The goal is to reduce the manufacturing cost of millimeter wave transceivers and to implement the cost savings improvements on the adopted baseline MLRS-TGW program. High electron mobility transistor (HEMT) monolithic receiver chips are planned for W-Band receivers, while MIMIC-developed heterojunction bipolar transistor (HBT) chips are planned for use in the Frequency Agile Source (FAS) and the intermediate frequency (IF) receiver. This MANTECH task will also use technology transfer from an Air Force Industrial Modernization Incentive Program (IMIP) project to implement hot isostatic pressing technology to produce the millimeter wave transceiver housings. In addition, this task will significantly increase fire support weapon system capabilities necessary for surge and mobilization threats.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

Laser radars and associated technology are being developed by NASA for atmospheric sensing and remote sensing from space, by the Environmental Protection Agency (EPA) and DoE for pollution and effluent monitoring, and by the Federal Aviation Administration (FAA) for windshear detection and velocimetry. NASA is currently developing laser remote sensing techniques using tunable laser sources. Picosecond laser technology is also being developed for satellite-based imaging of topological features with millimeter-scale resolution.

NIST has developed near-field antenna measurement techniques for the characterization of high performance antennas including phased arrays, microstrip elements, and ultra low sidelobe antennas. Measurements are available from 1-60 GHz providing gain, pattern, polarization, and element excitation for arrays. Wideband pulse techniques are being developed for antenna parameter and scattering measurements for microwave absorbing materials.

2. R&D in the Private Sector

Significant industrial R&D has occurred on high-efficiency diode laser pumping of solid-state lasers. Synthetic aperture radar and multispectral sensors are being pursued for commercial use in earth resource mapping.

University research efforts related to sensitive radars center on materials research, electromagnetic propagation and phenomenology studies, and basic physics work. The many independent efforts ongoing can contribute to specific sensitive radar programs.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified.

- Development of extremely wideband radar, wideband microwave sources, and antennas
- Active element arrays, including conformal arrays
- Beam steering, application of coherent laser diodes, laser radar

- Development of improved techniques for microwave and millimeter-wave radiometry.

In general, the United States is the world leader in all aspects of sensitive radar technology. The table below provides a summary comparison of U.S. efforts and those of other nations for selected key aspects of the technology.

The Soviet Union has maintained an active program in laser remote sensing for a number of years. The Soviet approach to laser radar technology has been advanced and innovative, encompassing such concepts as nonlinear laser radars based on coherent antiStokes Raman spectroscopy and optical parametric oscillator technologies. Presentations by Soviet researchers have even suggested the use of nonlinear photorefractive materials for high-resolution remote imaging. Even though Soviet thinking on laser radar technology appears advanced, their relevant technology base is well behind current US capabilities.

The UK, France, and Germany report ongoing efforts in synthetic aperture radar and inverse synthetic aperture radar technology, as well as basic programs in techniques for distinguishing targets of interest in high-clutter environments. There is significant R&D on coherent radars in the UK and in synthetic aperture radar imaging at the German Aerospace Research and Development Center. British Aerospace has developed a smart mortar projectile based on sensitive radar techniques.

Both Japan and the UK have microwave device and subassembly technologies with the potential to contribute to development of active element arrays. Recently, however, France has demonstrated a state-of-the-art capability in advanced techniques for antenna testing.

The UK has a significant effort in laser radar technology; Canada, France, and Germany also have strong ongoing programs. All of the major European countries have small programs in the use of laser radars for remote sensing with Germany and Sweden currently being the most active. France and Germany are actively pursuing joint investigation of the use of laser radar for helicopter detection and recognition.

Both France and Norway are studying the use of radar imaging techniques against surface targets (ships, armor, etc.). Sweden appears to have a significant effort covering a wide range of topics relating directly to NCTR. Of particular note is a program involving the characterization of aircraft target features with a CO_2 laser radar.

Japan possesses a large data base of practical knowledge on laser radar capabilities for remote sensing applications. The only area in which Japan has a clear disadvantage is in the development of the high-power laser sources needed for long-range target imaging and identification.

2. Exchange Agreements

Radar is the subject of a high level of exchange at all levels. The NATO Defense Research Group (DRG) programs in long-range research for air defense and in electronic warfare concepts and technology provide mechanisms for exchanges of fundamental information relating to radar requirements and design. The program in physics and electronics also provides a mechanism for supporting advances in materials and components critical to implementation of active conformal arrays. The Technology Cooperation Program (TTCP) has a large number of radar-specific exchanges that provide mechanisms for applicable exchange activities in generic radar system design, signal processing, and radar performance modeling, as well as in specific areas such as electronically agile radar, OTH radars, and radar sensors for RPVs.

Summary Comparison — Sensitive Radar

Selected Elements	USSR	NATO Allies	Japan	Others
Development of extremely wideband radar, wideband microwave sources, and antennas	□□□□ ○	□□□ ○	□□□ ○	
Beam steering, application of coherent laser diodes, laser radar	□□	□□□ ○	□□□ ○	□□ [a] Sweden
Active element arrays conformal antennas	□□	□□□ ○	□□□ ○	
Overall[b]	□□	□□□ ○	□□□ ○	□□ Sweden

[a] While not predominant in any key aspect of this technology, Sweden has reported some interesting research in target characterization with high-resolution laser radar.

[b] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

- □□□□ broad technical achievement; allies capable of major contributions
- □□□ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
- □□ generally lagging; allies may be capable of contributing in selected areas
- □ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

- \+ Foreign capability increasing at a faster rate than the United States
- ○ Foreign capability increasing at a similar rate to the United States
- – Foreign capability increasing at a slower rate than the United States

Each of the Services also has a number of exchanges with NATO and other friendly nations in areas of specific interest. These provide a mechanism for general exchanges in radar, as well as in specific applications such as ground– and satellite–battlefield surveillance (including an exchange with Germany in phased arrays). Examples of technology exchanges include millimeter and microwave components (France), computational antenna design techniques (Spain), and radar target characterization (UK). The Army and Israel are entering into a cooperative development agreement for a counter artillery radar.

8. PASSIVE SENSORS

8. PASSIVE SENSORS

A. DESCRIPTION OF TECHNOLOGY

Passive sensors (i.e., sensors that do not emit radiation in order to find targets, but instead merely "listen" for them) will be increasingly important to counter future enemy reductions in observable characteristics across many frequency bands. Passive sensors do not divulge information about the host platform which can be exploited by an enemy. Stealthy systems employ passive sensors to detect, track, and identify objects/targets while maintaining their own covertness.

Technology Sets in Passive Sensors

- Passive seekers
- Advanced thermal imagers/IR focal plane arrays
- Infrared search and track sensors (IRST)
- Sensor integration for target acquisition
- Advanced passive antennas
- Passive RF surveillance/electronic support measures
- Passive acoustic surveillance
- Fiber optic sensors
- Superconducting sensors

Passive threat warning technology provides strategic or tactical alert so that defensive measures may be taken. These systems include radar warning receivers, laser warning devices, space-based electro-optic systems, and warning of passive electro-optic/infrared (EO/IR) guided missiles. EO/IR is particularly challenging and crucial to maintain U.S. force survivability as heat-seeking missiles proliferate. The Airborne Surveillance Testbed (AST, formerly Airborne Optical Adjunct) provides a much needed platform for testing EO/IR technology concepts along with atmospheric phenomenology effects.

Missiles guided by passive infrared seekers home on thermal energy emitted by the target. Infrared seekers are needed for smart, weapons. Imaging seekers using infrared focal plane arrays (IRFPA) allow target identification and optimal aim-point determination. Higher resolution in a smaller volume is needed to support advanced missile systems. Seeker cost reduction is vital to future weapon affordability.

Advanced thermal imagers use the infrared spectral region for surveillance, acquisition, identification, and weapon guidance. Thermal imagers are necessary for night operations and passive surveillance, but water vapor absorbs infrared energy, limiting thermal imaging through clouds. Thermal imaging may be used to detect and identify some reduced radar cross section targets. IRFPAs are critical components of most advanced passive IR sensors. An IRFPA is an array of individual infrared detector cells. Each cell translates into a sensor pixel. Thermal imagers are either scanning with a rotating mirror focusing the received thermal energy on a narrow (e.g., 1 or 2 by n) detector array, or staring using a larger dimension array (e.g., 256 x 256). The operating temperature of an IRFPA is typically below 100 degrees kelvin, depending on detector material and desired wavelength sensitivity. Improvements in cryocooler reliability, packaging, and efficiency are needed to support future IRFPA applications. There is also a strong requirement for readout, analog, and digital electronics associated with the IR passive sensors to be cooled to eliminate the wire connections.

Infrared search and track (IRST) technology will supplement or replace radar in many applications. IRST has a covertness advantage over radar but, like other infrared technologies, IRST has limited capabilities through clouds. IRST sensors are also more resistant to conventional electronic countermeasures (ECM).

Passive conformal arrays are matrices of RF receiver modules, mounted on or embedded in a structure, so that the array shape conforms to the platform shape. Antenna protrusion is minimized, which results in improved aerodynamics and a reduced radar cross section over conventional antennas.

Electronic Support Measures (ESM) exploit threat radar and radio transmissions. Passive RF sensors are used for target detection, localization, and identification. ESM sensors are often used in conjunction with other sensors, particularly radar, where ESM provides a complementary passive capability.

Passive RF surveillance and targeting techniques provide an important adjunct to IR and ESM in countering the small target threat in a complex EW environment over a wide surveillance area. This passive sensor suite will capture and sort enemy emission over the entire spectrum to enhance detection, track, and ID. These passive sensors will interactively complement sensitive radar capabilities via cueing and multisensor fusion to counter the advanced threats as well as decreasing surveillance system vulnerability through passive mode operations.

The integration of different sensor types or multiple wavelength bands has a synergistic effect. Information gathered by one sensor is used to confirm a low observable detection on another. An infrared sensor may be obscured, while a complementary millimeter wave radar provides target acquisition. A two-color infrared seeker may be applied effectively against multiple target types in a high RF countermeasure environment. The challenges in sensor integration include shared aperture design, optical/RF window development, and development of dual-band electro-optic detector array and diffractive optics that conform to aerodynamic surfaces and provide wide area apertures.

Acoustic arrays have long been used for submarine detection, localization, and targeting. As Soviet submarines reduce their radiated noise and quiet diesel electric submarines proliferate throughout the world, more sensitive acoustic arrays become increasingly important to U.S. maritime strategy. Acoustic (and seismic) arrays are also being used for detection and identification of aircraft, ground vehicles, and troop movements; however, increased understanding of the propagation of acoustic signals is needed for improved sensor performance prediction and acoustic path characterization.

Fiber optic sensor technology is being applied to a number of different sensor types to provide a low-loss, multi-channel, ECM proof, data link capability. Many improvements in acoustic arrays use fiber optic technology. Fiber optic gyroscopes will improve inertial guidance systems and reduce cost. Magnetic sensors also use fiber optics.

Superconductivity represents an emerging technology. Both high temperature and low temperature superconductors offer the potential for low noise, high sensitivity sensor components. Superconductivity will be applied to sensitive infrared detectors and RF receivers. Superconducting quantum interference devices (SQUID) will provide sensitive magnetic anomaly detection for use in anti-submarine warfare.

B. PAYOFF

1. Impact on Future Weapon Systems

a. Weapon System Performance

Passive sensing is a critical adjunct to U.S. anti-stealth efforts. The effective exploitation of passive sensors enhances U.S. system survivability even in high-threat nuclear environments. Multi-band passive electro-optical sensors can reduce the sensitivity of existing sensors to environmental and target signature variations. Integrated sensor approaches will allow for multiple functions and collection of multiple target signatures. Such capabilities are not now available.

The Army, Air Force, and Navy have a requirement to reduce near-field front-end signatures that interfere with the passive sensors of hypersonic missiles. Many of the background effects can be reduced by using diffractive optics mounted on the side surface of the missiles, but not protruding into the shock flow field. Testing of this concept with laboratory supersonic flow test facilities and missile-diffractive optic prototypes could quickly validate the utility of diffractive optic/sensor devices in this system.

U.S. Navy control of surface and subsurface ocean areas has been put at risk by rapid progress in submarine quieting and other submarine acoustic technologies. Advanced acoustic sensors are needed to counter this threat and regain an advantage over quieter submarines. A major effort exists in the development of large-aperture, high-gain passive acoustic arrays to enable long-range detection of quieter submarines.

Fiber optic sensors also support major improvements in anti-submarine warfare (ASW) surveillance as well as provide the basis for autonomous underwater vehicle guidance. Future acoustic towed arrays from surface ships and submarines require at least 10 times the number of acoustic channels in either multi-line or extra-long arrays. Fiber optic acoustic sensor arrays appear to offer the best approach for this application.

Fiber optic sensors embedded in structures will provide continuous coverage of critical internal variables (like stress and temperature) to evaluate structural performance. Further, fiber optic gyros offer order-of-magnitude lower cost for weapon and autonomous vehicle guidance. Fiber optic gyros are small, all solid state with no moving parts, rugged, and reliable. An order-of-magnitude improvement in accuracy over state-of-the-art gyros may be possible with fiber gyros incorporating ultra low-loss fibers.

b. Weapon System Logistics

As indicated, all aspects of passive arra[illegible] need to be investigated. New designs and approaches will have significant influence o[illegible] diagnostic, repair, sparing, and maintenance training needs. Future architectur[illegible]d maintenance concepts need to be designed, developed, and analyzed in parallel an[illegible]n a logistics needs perspective.

Improved passive sensor technologies will permit non-intrusive system performance evaluation and health-monitoring capabilities. Emerging passive sensor technologies have the potential of improving diagnostic capabilities and future systems availability. New technology applications in weapon systems do not yet have the operational experience of existing technologies. Passive sensor techniques can accelerate the capture of needed information, permitting improvements in diagnostics reliability, maintainability, and performance. Examples of new technology applications that will benefit from more experience include: specialized composite and high-strength materials; high-performance engines; advanced VHSIC and MIMIC modules; fault- and battle-tolerant modular architectures; and interdependent electromechanical and structural subsystems such as smart skins.

Goals and Payoffs — Passive Sensors

Sensor Type	Goal	Payoff
EO/IR sensors (including focal plane arrays)	• 100x more detectors per focal plane • Much greater producibility • High resistance diode detector arrays for high sensitivity • Low-noise signal processing on detector chips • Nondestructive in-process testing for affordability	• Enable passive sensor operation with very high resolution and good ECCM capabilities (e.g., for use in ship air defense) • Crucial to overall U.S. edge in satellite surveillance (real-time, high-resolution capability) • Crucial to tactical surveillance and weapon systems
Compact antennas	• Enable small high gain antennas to operate at lower RF frequencies • Lower profile • Reduced size and weight	• RF missile guidance systems that are effective against stealthy targets • Greater mobility • Stealth
Superconducting sensors	• Low-noise magnetic sensor	• Expanded range for magnetic detection of submarines
Diffractive optics/ sensors	• Non-protruding, look-ahead sensor systems	• Reduce the shock plasma background signatures in passive missile sensors
Fiber optic sensors	• Ultra-sensitive acoustic, magnetic, chemical, temperature, and other sensors	• Extended detection range • Lower cost, light-weight, highly reliable sensors
Multispectral sensors	• Techniques and database to exploit signatures across spectrum	• Counter stealth and ECM • Exploit full range of target observables
Sensor fusion	• 10x improvement in tracking accuracy • Effective target identification	• Greatly improved capability to engage targets
Microwave radiometry	• Tactical images	• Enable passive sensor operation at moderate resolutions in poor weather
Diagnostic sensors	• 10x less downtime	• Improved weapon system availability

Passive sensors represent an enabling technology that facilitates improvements of maintenance design quality over weapon system life cycles. Without the integrated application of this technology in weapon systems, the maintenance quality improvement rapidly stagnates as design and development energies are focused on the next systems. Only major and obvious faults are detected and resolved. The much needed diagnostic history data must be measured, communicated between maintenance levels, and fed back to the design improvement process.

2. Potential Benefits to Industrial Base

a. Manufacturing Infrastructure

Passive, full spectrum earth imaging systems are being deployed for numerous applications including: weather forecasting; oil and mineral exploration; crop health analysis; and climatic research and analysis. The economic impact of these imaging systems is expected to be in the billions of dollars.

IR focal plane array technology development has focused on DoD applications. Advanced focal plane arrays fulfill highly specialized tasks in industry, drug enforcement, fire fighting, medicine, and commerce but are not likely to be used in general applications. The exception is PtSi, the basis for high performance sensors costing less than $30K. Such sensors can be used for process control, manufacturing, security, and medical diagnostic systems. Development of low cost, uncooled IR detection technology, however, would greatly increase the potential for commercial application.

Space-based IR imaging sensors have been successful in earth and space science applications related to the environment and its changing nature. Information on pollutants and their propagation, derived from these passive sensors, will greatly assist in improving and maintaining the atmosphere and earth. Manufacturing efficiencies could also result from such data. A limited market for commercial exploitation exists for sensors used for spacecraft station keeping purposes, such as communication, weather sensing, and earth surveillance.

The availability of low cost, high efficiency IR sensor technology would find wide application in in-situ process monitoring and control. Potential applications could include real-time temperature monitoring and control of highly temperature dependent materials, refining applications and alloying processes; monitoring and control of temperatures during metal machining, sintering, and composite curing operations; and real-time analysis of chemical processes. Likewise, acoustic and seismic type sensors, already used in a variety of manufacturing applications, will find significantly increased applications.

Underwater acoustic arrays have limited private sector applications generally limited to off-shore oil exploration. Air propagated acoustic sensors may be useful in noise measurement and abatement efforts by communities surrounding airports or major construction zones.

Fiber optic diagnostic sensors can be used to assess system status and improve reliability and maintainability in many industries. Temperature sensors supporting built-in-tests can be used in automotive engines and most machines. Embedded fiber optic sensors would be useful in monitoring structural integrity of aircraft, nuclear reactors, manufacturing equipment, and other systems subject to fatigue or corrosion.

Magnetic sensors have applications in medicine. Nuclear Magnetic Resonance (NMR) imaging is a valuable diagnostic tool which stands to benefit from magnetic sensor improvements.

The sonar transducer/sensor industry has been an active part of the defense industrial base for 50 years, and has been traditionally structured around defense and offshore oil applications with a very minor sonar fishery application. Lead zirconate titanate is the best established material for source and sensor applications. The industrial base involved in applications of this technology, however, has been steadily decreasing due to a shrinking base of skilled manpower and procurement processes that effectively limit competition.

b. **Logistics Infrastructure**

Passive sensors in many forms are pervasive as diagnostic tools: high–temperature electronic sensors on engines; room–temperature sensors in built–in–test equipment on manufactured products; and providing the "eyes" for robots on the factory floor. The depot environment will reap substantial benefits from improvements in passive sensor technology in terms of increased accuracy, greater availability, and reduced repair costs.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Passive Threat Warning

(1) Objectives

Improve passive threat warning sensors used to alert U.S. forces to imminent danger such as incoming missiles, potential targeting by hostile fire control radars or laser designators, or strategic attack. These technologies are intended to enhance national and force survivability and enable effective use of countermeasures.

(2) Development Milestones

- In a manner analogous to radar warning receivers, laser warning devices alert air and ground forces to the presence of a laser rangefinder, radar, designator, or weapon and allow friendly forces to take appropriate countermeasures. Demonstrate miniaturized laser warning sensor and fiber optic laser warning sensor in FY 1991.
- Space–based, electro–optic and infrared sensors will provide indications of strategic attack through booster and bomber detection. Because of their use in strategic warfare, it is particularly important for space–based, electro–optic components to be radiation hardened. Demonstrate radiation–hardened detector subarrays for long wave (8–12 micron) infrared focal plane arrays in FY 1992.
- The use of optical components also provides enhanced radiation survivability. Demonstrate wide–field–of–view optical brassboard in FY 1993 and demonstrate optical interferometric techniques for space–based surveillance in FY 1995.
- The Airborne Optical Adjunct/Airborne Surveillance Testbed (AOA/AST) supports critical electro–optic and infrared sensor technology developments by collecting needed background data and providing a platform for evaluating advanced surveillance technologies. The system will be operational in FY 1992. Subsequent milestones in this area concern the collection of broad ocean area signature data to resolve critical strategic defense surveillance technology issues.
- Radar warning receivers alert forces to imminent danger such as incoming radar–guided missiles or targeting by hostile fire control

radars. They allow U.S. forces to take appropriate countermeasures. Survivability will be further enhanced by integration of radar warning receivers with appropriate countermeasures. A digital radar warning receiver will be demonstrated in FY 1994 and advanced receivers will be demonstrated in FY 1995.

- Passive electro-optic/infrared (EO/IR) guided missiles are becoming common, but are difficult to detect. EO/IR missile warning technology will detect these missiles so that countermeasures can be taken. An optical array/smart skins EO/IR warning system for use with an airborne conformal array will be demonstrated in FY 1991. The Silent Attack Warning System using ultraviolet reflectance characteristics is scheduled to be demonstrated in FY 1991 and a high-accuracy direction-finder using an ultraviolet sensor will be demonstrated in FY 1993.

b. Passive Seekers

(1) Objectives

Develop passive seekers to provide missiles with target acquisition, tracking, and guidance control inputs without emitting radiation which would allow the target to take hostile or evasive action. This feature is crucial to fire-and-forget weapons, smart/brilliant weapons, and missiles operating beyond the launch platform's line of sight.

(2) Development Milestones

- Infrared seekers detect heat radiated by the target, using imaging techniques to acquire and engage the threat. Investigation of platinum silicide and mercury cadmium telluride (MCT) detector arrays is underway for specific applications to take maximum advantage of the lower cost of PtSi. By FY 1993, typical IR backgrounds will be characterized and simulated for staring IRFPA sensors using non-uniformity compensation to ensure acceptable performance for a broad spectrum of application. A multiple mission imaging IR seeker will also be demonstrated in FY 1993.
- Aerodynamic heating of IR seeker domes increases as missile speeds increase. Improvement in dome technology is needed to support passive guidance of hypervelocity weapons. A high speed range test of a new IR seeker dome will be conducted in FY 1994. In FY 1997, DoD will demonstrate a MWIR/LWIR seeker window for flights at speeds greater than Mach 8.
- Anti-radiation seekers will counter hostile radars and increase survivability of U.S. forces by targeting enemy radars. Home-on-jam (HOJ) seekers can improve force operations by targeting sources of enemy countermeasures. These seekers complement radar or passive RF or IR. A prototype advanced microscan receiver for detecting radiation sources will be constructed in FY 1992. An elementary ARM seeker incorporating improved detection methods will be constructed in FY 1993. An electromagnetic radiation source elimination (ERASE) multimode seeker will be tested in FY 1994.

c. Advanced Thermal Imagers/Infrared Focal Plane Arrays

(1) Objectives

Develop high density, low cost, high performance arrays for infrared detector devices. Investigate alternative IR materials (III–V, quaternaries, SiGe) for LWIR sensors. Advanced thermal imagers provide infrared imagery needed for night operations, target identification, and passive surveillance. The use of two–dimensional infrared focal plane arrays (IRFPAs) in such imagers permits improved vertical as well as horizontal resolution and increased sensitivity.

(2) Development Milestones

- IRFPAs are arrays of infrared detector cells on a chip. An IRFPA can be used in either a staring or a scanning sensor. It forms an image in the same manner as the charge–coupled device (CCD) in most video cameras, except the IRFPA operates at infrared wavelengths. IRFPAs are used in passive seekers, infrared search–and–track systems, and passive surveillance systems. Larger focal plane arrays are needed for high resolution staring thermal imagers at longer infrared wavelengths; however, production yields of IRFPA devices are small. Improvement in IRFPA producibility will reduce weapon system cost and improve performance. A demonstration of arrays for a long–wave scanning forward–looking infrared (FLIR) device has recently been completed. In FY 1991, a producibility demonstration of a medium wave infrared (3–5 micron) HgCdTe array will be conducted.
- A very large–scale, high density IRFPA will be demonstrated in FY 1993. Such arrays contain hundreds of thousands of detector elements rather than the hundreds or thousands in current arrays. Cost effective producibility development, test, and evaluation for 106–element PtSi focal plane array, 480 x 4 and 64 x 64 element MCT IR focal plane arrays will be accomplished by FY 1992. Development, test, and evaluation of 960 x 4 MCT focal planes will be completed by FY 1993. High density monolithic focal plane arrays will be accomplished by FY 1997.
- IRFPAs operate at extremely cold temperatures, typically below 100°K. Reliable, cost effective cryogenic assemblies are needed to house the IRFPA and array electronics. The cryocooler is placed within a dewar. A standardized advanced detector/dewar assembly (SADA) is scheduled to be developed in FY 1992. A demonstration of a quick cooldown Joule–Thompson cryocooler is also scheduled for FY 1992. An advanced heat pipe for use in IRFPA cooling will be developed in FY 1994.
- Milestones are scheduled to be completed in both cooled and uncooled second generation scanning systems. The performance of a cooled 480 x 4 charge imaging matrix HgCdTe array operating in the 8 to 10 micron range is currently being evaluated. Delivery of uncooled IR manportable prototypes is scheduled for mid FY 1992. A high density uncooled focal plane array for man–portable systems and missile seekers will be demonstrated in FY 1993. A

demonstration of a high-density, two-dimensional staring focal plane array capable of simultaneous operation in multiple IR frequency bands is scheduled for demonstration in FY 1996.

d. Infrared Search and Track (IRST)

(1) Objectives

Develop IRST sensors to complement radar in an ECM environment, providing all weather capabilities, and to acquire and track both high and low flying or sea-skimming targets. IR clutter analysis and sensor modeling efforts such as the Infrared Analysis, Measurement and Modeling Program (IRAMMP) are needed to support future sensor technology and system developments. IRST capabilities to detect and track low observable targets are under investigation. IRST air-to-air and surface-to-air capabilities will improve platform survivability.

(2) Development Milestones

- An advanced technology demonstration of the Advanced Air Defense ElectroOptic System (AADEOS) is scheduled for completion in FY 1992. Work on a space-based IRST to detect low observable targets will begin in FY 1993.
- airborne IRST for use against ship targets will also be demonstrated in FY 1993. An advanced dual band IRST and an IRST adjunct to ESM will be tested in FY 1995.

e. Sensor Integration for Target Acquisition

(1) Objective

Develop sensor integration techniques to use information from multiple sensors or multiple frequency bands to detect, track, or recognize targets. Such techniques are particularly effective in detecting and tracking low observables targets or targets operating in a high countermeasure or adverse weather environment. Sensor integration can occur at several levels. Pixel-level integration combines images; feature-level integration combines target features such as size, moments, and apparent temperature.

(2) Development Milestones

- The integration of RF with passive electro-optic sensors includes active radar/IR devices for dual mode seekers. Work has already begun on the development of an IR/MMW dual mode seeker. Developmental work on a dome housing an IR/RF seeker will be completed in FY 1992.
- Several demonstrations of RF/passive electro-optic sensors are planned. A multi-sensor detection system for short-range ship defense and a ground-based second generation FLIR/MMW radar for multisensor-aided targeting (MSAT) will both be demonstrated in FY 1993.
- The airborne version of the MSAT will be demonstrated in FY 1994. Demonstration of the Rotocraft Pilots' Associate advanced target

acquisition multisensor fusion system are planned for FY 1996. A system integrating multispectral FPA, tunable Lidar, and MMW sensors will be demonstrated in FY 1997.

- Laser radar and FLIR sensors provide complementary information. The laser radar is able to measure distance and sharply define the edges of an object, while the FLIR is able to provide internal details. Laser radar/FLIR multisensor systems will be demonstrated in FY 1993 and FY 1997.

- Multiple bands also permit improved operation against obscurants and multiple target types. A field test of a multispectral FLIR will be carried out in FY 1993. A tunable dual-band infrared focal plane array will be tested in FY 1994. This array will use materials to measure emittance in both bands in the same detector elements. A shared aperture system operating in the IR and shorter wavelengths will be tested in FY 1997.

f. Advanced Passive Antennas

(1) Objectives

Develop advanced passive antennas to be used in electronic warfare and communications. Passive conformal arrays are electronically steered, phased arrays whose shape conforms to the mounting structure as opposed to conventional antennas which protrude from it. They offer reduced radar cross section and aerodynamic drag compared with conventional antennas. DoD is developing passive conformal arrays for signature reduction while maintaining platform sensor performance.

(2) Development Milestones

Development of hypervelocity vehicle technology requires optimization of system aerodynamics. DoD is developing conformal arrays to provide hypervelocity weapon guidance and aeronautical vehicle sensor capabilities while minimizing drag and maintaining covertness. A laboratory demonstration of an embedded multi-function antenna will be conducted in FY 1993.

g. Passive RF Surveillance/Electronic Support Measures (ESM)

(1) Objectives

Develop improvements in ESM to: counter a reduction in threat emissions; provide positive hostile identification which will reduce fratricide; and provide more accurate targeting and cueing information for weapon systems. ESM exploits enemy electronic transmissions to detect, locate, identify, and track hostile forces. ESM is used in ground-, air-, and sea-based sensor systems, often as a passive complement to other sensor technologies.

(2) Development Milestones

DoD is investigating application of several new technologies for ESM. These include Surface Acoustic Wave (SAW) and Time-Difference-of-Arrival (TDOA) techniques. In FY 1991, a SAW compression channel receiver will be demonstrated. A performance evaluation of the Advanced Relocatable Shipboard High Frequency (HF) Direction Finding (DF) using SAW and TDOA techniques will be evaluated in FY 1993.

h. Passive Acoustic Surveillance

(1) Objectives

Improve passive acoustic surveillance to restore ASW advantage and to detect and identify helicopters, aircraft, ground vehicles, and troop movements. Passive acoustic sensors use target generated noise to detect, localize, classify, and track a potential adversary. Passive underwater acoustics have for many years been the primary sensor technology for anti-submarine warfare (ASW). U.S. submarine detection/counter-detection advantage has dwindled in recent years due to quieting of Soviet submarines and the proliferation of quiet diesel submarines. Tactical radar and electrooptic sensors require an unobstructed line of sight to the target, but acoustic and seismic sensors have the potential for threat detection where hills, forests, or other obstacles may limit electro-magnetic sensors. Air propagated acoustic sensors will also contribute to low observable surveillance.

(2) Development Milestones

The increased threat posed by quieter submarines requires development of larger arrays to improve acoustic detection at lower frequencies. Large fixed and deployable arrays will detect and track threat submarines capable of launching ballistic and cruise missiles from both coastal and deep waters. Extensive use will be made of fiber optic sensors and data links to reduce cost and electronic noise. Experiments with progressively larger arrays are planned beginning with a 100-plus element array in FY 1991. An over-500 element array experiment will be conducted in FY 1992. In FY 1995, the Navy will conduct a fractal scale array experiment with over 1000 elements. The Navy will begin exploratory development of ultra-low frequency (ULF) sensors in FY 1994. In FY 1995, the Navy will test a fiber optic shallow water Advanced Deployable Array in FY 1996.

The principal thrust in tactical passive acoustics is toward larger arrays to improve low frequency response and support multi-static active acoustic reception. Fiber optic sensor technology will play a major role to reduce array cost, space, and weight and eliminate electronic array noise. In FY 1993, the Navy will complete at demonstration (ATD) of a fiber optic planar array. In FY 1994, an at sea test of a multi-line tactical towed array will be conducted. Also in FY 1994, the Navy will conduct surface ship trials of a volumetric towed array for submarines.

DoD is exploring the use of geophone and microphone array technology for acoustic/seismic detection of air and ground targets. Accounting for environmental effects, (e.g., temperature inversions, wind, and terrain) will provide a challenge for these sensors. Target identification, location, and tracking accuracy needs to be addressed. Testing of seismic/acoustic sensors for detection and tracking of low observable and low altitude targets will begin in FY 1991.

i. Fiber Optic Sensors

(1) Objectives

Advances in fiber optic technology offer potential cost, size, and weight reduction while improving performance in various sensor applications. Advance fiber optic acoustic sensor technology to develop larger low frequency underwater acoustic arrays, use of fiber optics embedded in composite structures, and use of fiber optic gyroscopes (FOG) to reduce guidance and control costs while maintaining weapon system performance. Environmental sensors using fiber optics and fiber optic sensors for monitoring system status are also being developed.

(2) Development Milestones

A fiber optic magnetometer will provide an order of magnitude improvement over conventional fluxgate magnetometers. A fiber optic magnetic array sensor (MARS) demonstration is planned for FY 1992.

DoD is developing smart composites for airframes and other structures which may catastrophically fail due to fatigue. Embedded fiber optics will measure the effects of stress and strain on the structure. A demonstration is planned for FY 1996.

DoD is developing fiber optic gyroscopes for reducing guidance and control system costs. In FY 1991, an inertial grade fiber optic gyroscope will be demonstrated. A fiber optic gyroscope on a chip that will reduce guidance and control space and weight requirements will be tested in FY 1992.

Fiber optic sensors are being developed to assess damage and monitor physical parameters such as temperature. A fiber optic flooding sensor testbed demonstration is planned for FY 1994.

j. Superconducting Sensors

(1) Objectives

Recent breakthroughs in high temperature superconductivity offer potentially significant improvements across a broad spectrum of sensors. Investigate high temperature and low temperature superconducting devices for use in sensitive infrared detectors and microwave receivers. Develop Superconducting Quantum Interference Devices (SQUID) for magnetic anomaly detection. Applications of superconducting sensors include electronic support measures, anti-submarine warfare, air defense, naval warfare, land warfare, and strategic defense.

(2) Development Milestones

DoD is developing superconducting IRFPAs with significantly lower noise characteristics than conventional IR devices. A LWIR superconducting IRFPA operation will be demonstrated in FY 1993. An all solid state superconducting FLIR will be demonstrated in FY 1995.

Low noise superconducting RF components and systems are being developed by DoD. A demonstration of superconducting components for electronic warfare applications will be conducted in FY 1993. A surveillance receiver will be developed by FY 1996.

DoD is developing superconducting magnetic anomaly detector (MAD) systems primarily for anti-submarine warfare and mine detection. A prototype LTS MAD system will be developed by FY 1994.

2. Technology Objectives

Technology Objectives — Passive Sensors

Technical Area	By 1996	By 2001	By 2006
Passive threat warning	• Demonstrate radiation hardened space-based EO/IR strategic threat warning sensors • Enhance low frequency response of radar warning receivers • Demonstrate passively guided missile warning technology • Demonstrate compact laser warning sensos	• Improve radar warning receiver DF accuracy (especially at lower frequencies) • Improve capability to detect/evade passive weapons	
*Advanced thermal imagers/IRFPA	• Demonstrate large-scale MWIP and LWIR detector array producibility • Integrated detector array, electronics, and dewars into standard assembly • Demonstrate high density uncooled RFP • Develop staring thermal imagers for NCTR and ATR • Develop space qualified 5-year reliable cryo-cooler • Demonstrate gamma suppression algorithms	• Demonstrate large-scale multiple color staring FPAs • Develop miniature low cost, integrated detector/dewar assemblies • Develop uncooled thermal imagers supporting NCTR and ATR	• Product LWIR FPAs needing conventional refrigerants instead of cryogenic cooling
Passive seekers	• Demonstrate imaging IR seekers for multiple missions • Demonstrate high speed seeker domes • Demonstrate multi-mode anti-radiation seekers	• Demonstrate dual band EO seekers supporting ATR capabilities for smart weapons • Demonstrate IR seekers and domes for hypervelocity weapons	
IRST	• Develop IRST for passive surveillance	• Demonstrate IRST using multiple color IR FPA for target acquisition and identification • Demonstrate space-based IRST demonstrate low observable surveillance capabilities	
Advanced antennas	• Demonstrate wideband; high accuracy DF antennas • Develop passive conformal arrays	• Demonstrate embedded multiple function antennas for hypervelocity vehicles	

Technology Objectives — Passive Sensors (Continued)

Technical Area	By 1996	By 2001	By 2006
Passive RF Surveillance/ESM	• Demonstrate ESM receiver improvements using TDOA techniques and SAW technology • Improve DF capability by two orders of magnitude • Develop bistatic ESM receivers	• Demonstrate ESM multiple sensor integration	
Sensor integration for target acquisition	• Integrate IR and RF devices for target acquisition • Integrate FLIR and laser rangefinder • Evaluate multi-spectral electro-optic sensors	• Integrate multiple color FPA, ladar, and RF sensors	• Develop flexible shared aperture, integrated active/passive sensor suites covering RF, visual, and IR spectral regions
Passive acoustics	• Evaluate detection limits of very large underwater passive acoustic arrays • Demonstrate multiple line tactical toward arrays • Demonstrate fiber optic underwater planar array • Evaluate air-propagated acoustic and seismic sensor array networks for low observable detection and tracking	• Develop ultra-low frequency underwater acoustic sensors • Demonstrate shallow water deployable fiber optic arrays • Develop network of remote acoustic and seismic sensors	
Fiber optic sensors	• Demonstrate fiber optic temperature flooding and magnetic sensors • Demonstrate smart composites • Demonstrate high quality, low cost fiber optic gyroscopes • Demonstrate multiplexed fiber optic sensor systems • Demonstration of fiber optic gyro of ESG accuracy	• Demonstrate LTS IR FPA imager • Develop HTS RF components • Demonstrate distributed fiber optic sensor (10x the number of acoustic channels used in 1990) • Demonstrate FOG incorporating ultra low-loss fibers (10x increase in accuracy over ESG)	• Develop HTS IR FPA • Develop HTS magnetic sensors • All optical surveillance and communications systems performing simultaneous operations with no individual function performance penalty • Distributed fiber optic sensor in full-scale development • Demonstrate FOG with 100x increase over ESG
Super-conducting sensors	• Develop LTS IR detector arrays • Develop LTS MAD systems • Develop LTS components for RF systems	• Demonstrate LTS IR FPA imager • Demonstrate HTS RF components	• Develop HTS IR FPA • Develop HTS magnetic sensors

3. Resources

Total S&T funding[8] for this critical technology is shown below:

Funding — Passive Sensors ($M)

FY87-91	FY92	FY93	FY94	FY95	FY96	FY97
2065	530	554	523	512	514	509

4. Utilizing the Technology

DoD programs that presently or may in the near future use emerging passive sensor technologies include the use of infrared focal plane arrays as an element in the development of:

- Forward Area Air Defense System
- Multisensor target acquisition systems
- Deep fire smart munitions
- Families of advanced small arms
- Advanced Tactical Fighter
- Increased soldier survivability
- Strategic Defense System
- Rotorcraft Pilots' Associate
- Heavy Force Modernization
- SSN 21
- AN/SQQ-89 Improvement Program.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

Infrared focal plane arrays (IRFPAs) form the basis for many of our future passive sensors. Current efforts are concentrating on the mid (MWIR), long (LWIR), and very long wavelength regions of the spectrum. The Air Force manufacturing technology (MANTECH) program has two MWIR HgCdTe detector array programs aimed toward demonstrating a two million pixel per year manufacturing capability and reduce the cost of the arrays by a factor of ten or more. The total cost of these programs is $29 million over a four-year period, and the programs will be completed in 1991. These programs are directed toward strategic applications.

Very large scale platinum silicide (PtSi) arrays (300,000 detectors) have been developed for short and medium wave infrared applications (SWIR, MWIR). This technology is ready for producibility demonstration. The Air Force is investigating Iridium silicide (IrSi)

[8] Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

as an alternate LWIR detector material. IrSi operates at 45 degrees Kelvin; arrays as large as 256 x 256 have been demonstrated, but the technology is still immature. Recent advances in III–V–ternary and quarternary semiconductor materials have demonstrated the concept of superlattice and multi–quantum well structures fabricated from these materials for LWIR sensors. The Defense Advanced Research Projects Agency (DARPA) IRFPA program is establishing a manufacturing capability for MWIR PtSi arrays and LWIR HgCdTe arrays for tactical applications. The Strategic Defense Initiative Office (SDIO) is establishing two pilot lines for production of extrinsic silicon detector arrays for very long wavelength applications. The Army manufacturing technology thrusts in night vision and electro–optics and missile seekers are pursuing processes for the production of IRT night vision and FLIR systems, and smart munition seekers and electro–optic sensor production.

Cooled infrared focal plane arrays fabricated in mercury–cadmium–telluride are not, nor are they likely to become, commercial items. Their manufacture requires specialized processing similar to, but not identical with, silicon and III–V semiconductor processing. The high quality material and specialized processing required, therefore, will need special manufacturing support from DoD. Additionally, the readout electronics required for HgCdTe detectors are lacking due to off–set voltage requirements of the detectors. The arrays developed with silicides use many standard silicon process technologies, and thus will be partially supported by the substantial commercial base.

2. Projected Industrial Capabilities

The focal plane array industry could grow significantly if future demand increases as projected. For U.S. military applications alone, approximately 140 weapon systems could require FPA detectors in some capacity over the next 10 years.

Ongoing HgCdTe IRFPA programs will provide the basic manufacturing skills required for application of that technology. However, there may be other manufacturing programs required to address system specific requirements for increased uniformity and detectivity for the detector arrays. In–process and acceptance testing is a major cost driver for HgCdTe IRFPAs. Methods for decreasing the time and increasing the throughput for IRFPA testing are required. The DARPA IRFPA programs are specifically addressing tactical applications. Additional work may be required to establish a HgCdTe LWIR manufacturing capability for the lower background strategic applications.

Underwater acoustic arrays have limited private sector application. As commercial items, they are primarily used for off–shore oil exploration. Air–propagated acoustic sensors may be useful in noise measurement and abatement efforts by communities surrounding airports or major construction zones.

Fiber optic diagnostic sensors can be applied to assess system status and improve reliability and maintainability in many industries. Temperature sensors supporting built–in–tests can be used in automotive engines and most machines. Embedded fiber optic sensors would be useful in monitoring structural integrity of aircraft, nuclear reactors, manufacturing equipment, and other systems which are subject to fatigue or corrosion.

Magnetic sensors may have applications in medicine. Nuclear Magnetic Resonance (NMR) imaging is a valuable diagnostic tool which stands to benefit from magnetic sensor improvements.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

The DoD efforts in developing passive IR technology are coordinated with both NASA and industry. There are a small number of research efforts at universities and at the national laboratories on superconducting sensors (both RF and IR) and strained superlattice detectors. The only area in which current non-DoD funding is significant in supporting related research is in materials development for superconductors. NASA has astronomy sensor requirements from ultra-violet to LWIR to support planetary and other space exploration projects. NASA efforts in cryogenic cooling for spaceborne sensors are similar to those of DoD. DoE laboratories use fiber optic sensors in many applications.

Calibration facilities have been developed at NIST to characterize optical radiation detectors from the near-UV to the near-IR spectral regions with direct reference to the Nation's radiometric scales. A new facility is under development to enable characterization of detectors and provide detector standards in the far infrared region to approximately 30 micrometers. A low background infrared (LBIR) calibration facility has also been developed to support the DoD calibration effort for infrared focal plane arrays. The capability is being enlarged to provide calibration of new, low background IR detectors being developed for possible employment as sensors.

NSF supports research in the areas of silicon microsensors, biosensors, IR/far-IR detectors, and microelectromechanical devices. Support is provided primarily through ongoing programs in engineering.

2. R&D in the Private Sector

University research on passive infrared sensors has generally addressed basic issues in material growth, surface physics, and advanced device concepts such as single and multiple quantum wells and superlattices. Process technology has been almost exclusively supported at industrial laboratories. Continued and expanded support of the establishment of II-VI processing technology at selected university research centers is an important element of the development of critical, high-yield processing technology. University efforts supporting passive sensor technology development include R&D in superconducting sensors (both RF and IR) and strained superlattice detectors. Such programs are often funded through DoD or DoE. University work has shown high temperature superconductors at 125K which will improve the sensitivity of bolometric arrays at thermoelectric temperatures and which, therefore, could be significant for future infrared imaging. Other university research related to passive sensor technology includes fundamental studies in optoelectronic materials and basic physics research and phenomenology.

Small Business Innovative Research (SBIR) programs are being undertaken to acquire knowledge critical to the achievement of higher yields in the production of HgCdTe infrared focal plane arrays (IRFPAs). These programs will provide insight into the role of precipitates, dislocations, and subgrain structure on the suitability of epitaxial material for IR detectors and their impact on yield and performance degradation. Studies are being conducted to determine the mechanisms by which defects form, the temperature of formation, and their behavior during subsequent annealing.

Further SBIR work supporting uncooled IR detector technology is directed at improving the temperature coefficient of resistance of bolometric materials. An advance in ferroelectric materials is also being investigated that has application to uncooled detectors.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified.

- Material processing and fabrication of large-scale IR focal plane arrays
- Full militarization of SQUID sensors
- Fiber optic sensor systems.

Opportunities for cooperation in niche technologies may be realized in Japan, whose solid-state technology could clearly make significant contributions. The Japanese, despite their limited experience in military sensors, are beginning to contend in second-generation IR imaging and advanced EO sensors, with the advanced development of a 1000x1000 element Schottkey-barrier device. While such devices have inherently lower quantum efficiencies than competing compound semiconductor detectors, they offer significant offsetting improvements in terms of uniformity of response and output signal to noise.

Japan has ongoing work in vapor phase growth of HgCdTe but is lagging in the application to focal plane arrays. They have significant work in platinum silicide, and 512x512 detector arrays are commercially available but are expensive.

The Japanese are ahead of the United States in the area of multi-band-capable components using dissimilar compound semiconductor materials (e.g., GaAs with InP). While this work has been principally directed towards commercial telecommunications, the underlying materials and device fabrication techniques might contribute to future military sensor programs.

An area likely to lend impetus to Japanese developments is their space program. Japan plans to launch a number of advanced earth surveillance satellites in the 1990s.

Japanese expertise in optical fibers and related components also provides an excellent base for advancing technology of fiber optic sensor system (FOSS). Their lack of direct experience in military FOSS is offset by the strength of the basic technology infrastructure. Israel and Sweden also have significant programs, which contribute to novel applications and device technology.

European countries have continued their development of HgCdTe detectors. Literature from Poland indicates continued progress in improved performance. The Soviets are believed to have developed a FLIR using a linear HgCdTe detector array for use on tanks and possibly helicopters. There is little evidence, however, of mass production and deployment of FLIR systems to date.

Work in Poland includes vapor phase growth of HgCdTe, but with the effort in focal plane arrays considerably behind the United States.

The Soviet Union and the Eastern European countries have not reported on the uncooled detectors, although interest in these devices probably exists.

The Soviets are pursuing Stirling cycle coolers for space applications; however, they lag domestic development in terms of long lifetime and high reliability. They have published results of innovative concepts utilizing pulse tube refrigerators and appear to be far ahead of the United States in this technology.

Summary Comparison — Passive Sensors

Selected Elements	USSR	NATO Allies	Japan	Others
Material processing and fabrication of large-scale detector arrays	□□	□□□□ ○	□□□ ○	□ Israel
Full militarization of SQUID sensors	□□	□□	□□	
FOSS	□□	□□	□□□ ○	
Overall[a]	□□	□□	□□□ ○	□ Israel
	[a] The overall evaluationi s a subjective assessment of the average standing of the technology int he nation (or nations) considered.			

LEGEND:

Position of other countries relative to the United States:

□□□□ broad technical achievement; allies capable of major contributions

□□□ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions

□□ generally lagging; allies may be capable of contributing in selected areas

□ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

+ Foreign capability increasing at a faster rate than the United States

○ Foreign capability increasing at a similar rate to the United States

— Foreign capability increasing at a slower rate than the United States

Silicon thin-film impurity band conduction (IBC) technology was discovered in the United States and is an area where we have a lead. Silicon research by our allies is primarily on bulk materials. There are reports that German industry is working on silicon IBC devices, and the high overall level of semiconductor technology in Japan could offer some contributions in this area.

NATO allies have expertise in second-generation focal plane array fabrication. The British have developed 128x128 switched multiplexer arrays imaging in the 8–12 micron region. The French have developed a producible liquid phase epitaxial technology from a tellurium melt which provides arrays imaging in the 8–12 micron region. The long wavelength cut-off is limited by the charge handling capacity of the silicon charge-coupled device readout processor. Arrays of 288x4 and 64x64 have been made and are being acquired by DoD for evaluation. Research and development of HgCdTe is conducted by the British, French, and Germany is presently producing the linear HgCdTe detector array used in the U.S. modular FLIR.

The British are well behind in production and test capability but are very competitive in passivation (encapsulation) techniques and understanding of HgCdTe detectors. The Japanese have reported IR detection using superconducting materials; however, it does not appear to be a concerted effort. The total amount of R&D in HgCdTe materials in Europe has been small compared to ongoing U.S. efforts. The British have developed pyroelectric materials for use in infrared sensors and British imaging systems are available commercially. The resolution and uniformity of the British common module FLIRs (optimized for input to processors) exceeds U.S. systems. The U.S. common module FLIR has higher sensitivity and is best for human viewing application. The Australians have a low resolution bolometric system used with smart processing for perimeter surveillance. The sensitivity is considerably below that obtained in the United States.

Only the British have a space-qualified cryocooler. This Stirling cooler has been life-tested for a five-year equivalent period and is currently being produced. This technology is not yet available to the United States. Philips (Netherlands) and Germany have been identified as sources of closed/split-Stirling cycle coolers for IR detectors. Israel has advertised a cooler similar to that currently used on the TOW night sight, but details of its performance and reliability are not known. The Italians are aggressively working on magnetic refrigerators and have tested a no-moving-parts cooler.

While the United States continues to lead in the design and packaging of SQUID devices for military use, other countries are showing increasing capabilities. These are discussed in Section 19, Superconductivity.

2. Exchange Agreements

There is a high level of exchange activity in virtually all aspects of passive sensors. The NATO Defense Research Group (DRG) Long-Term Scientific Studies and LongRange Research Related to Air Defense, Optics and Infrared Technologies, and Electronic Warfare Concepts and Technology provide mechanisms for some level of exchange of fundamental requirements and scientific information in passive electromagnetic, battlefield acoustic, and electro-optical/IR sensors. The DRG on identification of submarines includes exchanges on ASW towed arrays.

The TTCP also provides mechanisms for a range of applicable exchange activities. Specific topics under TTCP include IR and EO sensors, undersea warfare and sonar, EW signal processing and radar emitter identification (passive intercept techniques).

Each of the Services has exchanges in passive sensors, primarily with NATO and other friendly nations. The Services also have exchanges in specific application of passive sensor technology, such as passive acoustic and seismic detection for ground systems and counter-intrusion detection, space-based IR surveillance, and airborne ASW acoustics. In addition to these directly related programs the Services have exchanges in such topics as sensor techniques for limited visibility, radar signature and target characteristics, optical (including IR) propagation, and millimeter-wave measurement techniques.

9. SIGNAL AND IMAGE PROCESSING

9. SIGNAL AND IMAGE PROCESSING

A. DESCRIPTION OF TECHNOLOGY

Signal processing is the technology used for extracting the relevant information from signals received from sensors (electromagnetic, acoustic, etc.) and presenting usable information for use by human operators or machines. Because of improved signal processing, decision-making processes increasingly are being automated. Such automation of human functions in the highly dynamic and hostile environment of future warfare will enable standoff weapon engagement capabilities not otherwise possible. In many cases, signal processing technology has increased the trustworthiness of the extracted information to the point that a machine can be relied upon to make consistent decisions.

Signal processing technology combines advanced electronic devices, algorithms, and computer architectures to meet the increasing numbers of threats, counter stealth, automate operations, avoid overloading human operators, and process more complex signals from advanced sensors. The signal processing problem is complicated by intentional or unintentional jamming, decoys, and stealth technology.

The advance of signal processing technology depends on concurrent development of other critical technologies, such as semiconductor materials and microelectronic circuits, software producibility, parallel computer architecture, machine intelligence and robotics, photonics, simulation and modeling, sensitive radars, passive sensors, and data fusion. Combination of these technologies in weapon systems has and continues to provide improved capabilities.

Technology Sets in Signal and Image Processing

- Algorithm development
- Artificial neural networks
- Hybrid optical-digital techniques
- Control of phased arrays

The application of artificial neural networks to signal processing is in its infancy. The ability of neural networks to perform pattern recognition is presently being investigated for target detection, identification, and classification in synthetic aperture radar (SAR), electronic warfare (EW), intelligence, anti-submarine warfare (ASW), and cartographic and imaging systems. Robotic developments using neural network technology are also being investigated for manufacturing applications. A near-term goal for such efforts is to give manufacturing tools more subtle sensory motor skills and perceptual reasoning. Autonomous robotic devices that can operate in hostile environments (e.g., chemical, biological, and nuclear contaminated areas) are a longer term goal.

Hybrid optical-digital signal processing techniques show promise for SAR, radar, EW, and sonar sensors. Such techniques typically are used in conjunction with other signal processing techniques, such as adaptive artificial intelligence or neural network techniques.

Control of phased arrays (both radar and acoustic) is heavily dependent on signal processing technology. The focus of DoD R&D is to provide sufficient computation capability to handle large aperture array systems, especially conformal arrays contoured to the shape of an aircraft's skin or a ship's hull. The Air Force, Navy, DARPA, and SDIO are working on digital beamforming capabilities to support a variety of space, air, and surface detection/tracking systems. An Air Force effort is to apply photonic technology to the control of phased arrays in order to increase the speed of radar control. The Navy and DARPA are focusing their attention on ASW applications with emphasis on enhancing acoustic array beamforming using optical technology and multi-dimensional arrays.

DoD algorithm developments are focused on optimizing weapon system performance under today's complex battlefield conditions. A primary DoD area of concern is to apply the correct algorithms to non-cooperative target recognition (ATR) and ATR systems. Continued rapid growth in hardware complexity, versatility, speed, memory capacity, and affordability have opened the door to algorithmic approaches which have heretofore been too computationally intensive. Most conventional signal processing systems continue to adhere to a classical sequence of preprocessing, filtering, detection, segmentation, characterization, classification, and tracking. Given the capabilities of modeling computational hardware, a wider variety of algorithm approaches are now being pursued:

- *Correlation or matched filter techniques*: Correlation classification involves taking the cross correlation between representations in one-, two-, or three-dimensional space. The correlations must be taken for all target aspect angles, sizes, and positions of interest in the surveillance field. The correlation process tends to be computationally intense and is therefore well suited to multi-dimensional optical correlators. Model-based classification is a recent variant of correlation classification.

- *Adaptive multi-dimensional processing*: This approach takes advantage of the multi-domain sensor observables (spatial, temporal, spectral, and polarization) in the target environment by providing full adaptation in all these domains. The approach is implemented through multiple parallel multi-dimensional filtering banks that realize matched filter performance (versus "best fit" performance) of a single filter. This adaptive approach allows the implementation of high throughput VHSIC devices in deterministic systolic and highly flexible architectures (e.g., in reduced instruction set computers (RISC)) to handle optimally the processing problem. This approach allows for multi-spectral data association and correlation between sensor types to significantly enhance detection, tracking, and identification.

- *Model-based approaches*: This involves reduction of target images to only those features significant to the correlation process used for example, using only line segment orientations and their relative locations. These features are then extracted and passed to a knowledge-engineered process of logical operations which identifies one of a set of target classes. With this technique, it is also necessary to accommodate the wide variations in target aspect angle, although the process can be made invariant to apparent target size.

- Alternate basis sets: Mathematical research done over the last five years has resulted in a number of new algorithms being discovered which dramatically reduces the computational effort involved in the processing of information and signals. Compactly supported wavelet structures are an example. Wavelets are families of basic functions in terms of which other arbitrary functions can be represented with far greater accuracy and efficiency than the Fast Fourier Transform. Initially developed for performing multi-resolution analysis on digital imagery, a flood of additional applications are now apparent including audio and video compression, covert communications, and the fast solution of partial differential equations.

B. PAYOFF

1. Impact on Future Weapon Systems

Application of signal processing technology to conventional weapon systems offers important advantages, such as reducing operator workload (e.g., sonar, fire-and-forget weapons), improving system performance (e.g., increased kill probability, tracking additional targets, operating unabated in a hostile environment), and performing new functions (e.g., autonomous vehicle guidance and control). Signal processing technology enhancements continue to automate more weapon system functions. The payoff of automation includes diminishing weapon systems life cycle costs associated with alleviating operator stress, reduction of operator and maintenance manpower, and lessening the training necessary to operate and maintain weapon systems. The table on the next page summarizes the potential payoff of emerging signal processing capabilities.

Artificial neural network technology offers the advantages of significantly improved tracking, classification and identification by optimizing data base searches with incoming target data and by separating actual target signals from background noise, decoys, and jamming signals. As neural net technology evolves, it will be incorporated into autonomously guided missiles, improving lethality by recognizing real targets from decoys/background noise. Command and control systems will employ neural decision aids. Imaging and reconnaissance systems will be able to automatically detect targets of interest from two- or three-dimensional image data. The capability of sonar, radar, and fire-and-forget weapon systems of recognizing real targets from decoys will be greatly enhanced. Robotic devices will be capable of greater dexterity in their motor skills, thereby expanding the automation of the manufacturing process and promoting the use of remote robotic devices in hazardous environments (e.g., minefields, deep sea operations, chemical warfare).

To provide low probability of intercept (LPI), higher gain for greater range and/or successful operation in a noisy environment (jamming, high use bandwidth), larger multidimensional arrays are being designed. Hybrid optical-digital techniques offer the faster control necessary to operate these systems. Electronic control of phased arrays eliminates mechanical steering of sensors, thereby improving a sensor system's inherent reliability. Digital beamforming, the primary control process for phased array systems, provides the means to easily vary the system's bandwidth, and to optimize generation of very narrow beams with very low sidelobes and steerable sidelobe nulls. This capability allows a system (e.g. communications, radar) to have a low probability of intercept (denies a signal to a known enemy), to tune out noise and jamming, to detect stealthy targets, and to give accurate azimuthal and elevation target information.

Goals and Payoffs — Signal and Image Processing

Targets	Current State of the Art	Long-Term Potential
Fixed high-value ground targets (bridges, hangars)	• Ready for engineering development (laser and IR techniques)	• More robust techniques, i.e., all weather, night
Ships and submarines at sea, or in harbors	• Technology available (SAR/ISAR) for advanced development	• Near automatic recognition capability
Moving targets in moderate/low clutter (aircraft against clear sky)	• Technology potentially available using noncooperative target recognition techniques (e.g., IR conventional or MMW radar)	• Move to more automation of recognition function
Advanced atmospheric target in high clutter and EW environment	• Limited capability exists	• Fusion of multispectrual sensors required with high-resolution processing
Unobscured fixed land targets in benign backgrounds (tank in desert)	• Within state of the art for cueing (IR) • Ready for advanced technology demonstration	• More robust cueing and eventually automatic recognition • Multisensor approaches and laser radar
Moving targets in cluttered background and under the influence of obscurrants, weather, and countermeasures	• Still a subject of research or early exploratory development at the testing and signature collection stage	• Not likely to achieve full automation • Pilot will remain in the loop • Improve robustness to environmental conditions
Fixed land targets in high cluttered backgrounds/partially obscured (tank in bushes or trees)	• Still a subject of research or early exploratory development	• Success uncertain • Technology will evolve with this as a future goal
Secure and survivable communication	• Modest individual standalone capabilities exist	• Robust survivable integrated networks
Strategic relocatable targets	• Promising techniques emerging (SAR/ISAR)	• Limited capability possible • Capability against obscured targets and countermeasures much less certain
Quiet submarines	• High-gain, volumetric arrays under evaluation • Full spectrum signal analysis	• Capability against quiet targets
Moving targets in space on earth clutter	• Detection with low-sensitivity sensors	• Automated detection, acquisition track, and kill assessment

Algorithm development for automatic target recognition (ATR) capabilities are being embedded into numerous systems. In reconnaissance and imaging systems, much progress has been made in the area of image segmentation, feature detection/extraction, and pattern recognition of static objects. This ATR ability significantly reduces operator and photo interpreter workload. Present ATR developmental efforts will lead to weapon systems with automated detection capabilities to counter concealed (e.g., camouflage, foliage) targets, and deception techniques (e.g., decoys). This development will improve fire-and-forget weapon lethality and will also reduce operator workload for EW, sonar, radar, SAR, battle management, reconnaissance, and intelligence systems.

2. Potential Benefits to Industrial Base

Signal processing technology is also applicable to the industrial base. Signal processors are being developed to recognize handwritten characters for automatic zip code recognition systems and for handwritten data entry to computer systems. This will allow entry of data and text to computer and word processing systems. Speaker-independent voice and speech recognition systems are being developed. These capabilities will allow vocal entry of data and text into computer and word processing systems. The commercial impact of such capabilities could be enormous. Seismic signal processing by means of neural networks for the detection of natural resources (oil and gas) and possibly earthquakes will be extremely useful, if proved feasible. A number of emerging biomedical applications of signal processing include computerized axial tomography (CAT) scanners, electrocardiogram (ECG) analysis, and in prosthetics. Neurocomputers, which are used to emulate many of the neural network models, are creating a new industry to solve problems that conventional computers have not successfully or efficiently solved.

An indication of the rapid evolution of signal processing in the industrial base includes the proliferation of 386-based personal computer general purpose digital signal processing software packages. These provide the ability to graphically configure digital processing building blocks (e.g., filters, transforms, etc.) and apply these functions to input signals. Other applications include airline scheduling, commercial banking, economic forecasting, environmental prediction, and remote sensing image analysis.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Artificial Neural Networks

(1) Objectives

Artificial neural networks may within 10 years signficantly enhance the capabilities of a wide range of weapon systems by endowing them with the ability to learn from experience. Specific program goals are typically guided by the intended application (e.g., higher resolution radar, improved weapons targeting). However, in each case, the objective is to use the intuitive learning abilities inherent in artificial neural networks to improve weapon performance. This improvement will be accomplished by automating the decision process; negating the effects of jamming, decoys, concealment, and stealth; and compensating for continuously changing environmental conditions.

(2) Development Milestones

- Work has begun on developing microchip sets and optical devices designed for neural network application. Between FY 1992 and FY 1994, computer simulations of neural networks for seismic, sonar, speech processing and automatic target recognition will be completed.
- A Congressionally mandated consolidation of the Services' robotic development efforts has been initiated (see also Critical Technology on Machine Intelligence and Robotics). Robotic applications are presently limited to applying learning abilities and motor skills to manufacturing technology. In FY 1994, a demonstration of rudimentary robotic prototypes performing perceptional and reasoning tasks will be the first step in developing robotic devices that can semi-autonomously operate in hazardous environments (e.g., chemical warfare sites, minefield clearance, deep sea operation).
- Neural network-based voice recognition efforts are concentrating on developing universal speech monitoring techniques for

understanding a growing library of variable speech patterns from different people under various conditions (e.g., stress, excitement). By FY 1992, real-time recognition of continuous speech with a 1,000-word vocabulary, adaptable to new speakers, will be simulated in the laboratory using large computers.

b. Hybrid Optical–Digital Techniques

(1) Objectives

Optical devices still suffer from dynamic range limitations. Until photonics technology significantly surpasses digital technology, a hybrid optical–digital technology will be applied. This technology is emerging as individual photonic devices become available for integration into digital and hybrid systems. It will provide the faster processing speeds necessary to handle increasingly complex signal waveforms in dense signal environments.

(2) Development Milestones

- Design will begin in FY 1991 on a hybrid optical–digital processor for use with a SAR system, employing neural networks and model-based algorithms to provide automatic target recognition (ATR) capability. By FY 1993, initial design will begin on a combat identification system employing a trillion operations per second optical processor. Also in FY 1993, an investigation will begin to identify the capabilities of adaptive self-learning, optical neural computers.

c. Phased Arrays Control

(1) Objectives

Phased arrays of sensors are electronically controlled through individual activation rather than through mechanical steering of an entire array. Signal processing enhancements are needed to improve the performance of emerging phased array systems. They provide the capability to handle an increased number of array elements in variable multidimensional configurations. Selecting different array configurations can reduce jamming susceptibility, lower probability of intercept, and provide higher gain, and greater spatial resolution. A second objective is to improve the speed and EMP survivability of phased arrays through the use of optical techniques.

(2) Development Milestones

- Digital beam–forming techniques are the primary method to control conformal arrays which are contoured to the shape of an aircraft's skin or a ship's hull. These arrays reduce radar cross section and aerodynamic drag. The development of an airborne conformal array radar using digital beam steering control techniques is scheduled to begin in FY 1991. A demonstration of conformal array digital beam–forming will occur in FY 1994. This conformal array radar will be flight tested in the beginning of

FY 1996 to determine its ability to detect and track low observable targets in a jamming environment.

- In FY 1992, digital beam–forming techniques will be applied to phased array fire control radars. The use of a wideband phased array radar for cued fire control will be demonstrated in FY 1993.
- The optical control of phased arrays will provide the increased speeds necessary for the large, multidimensional arrays envisioned for the next century. The fabrication of an optical processor for phased array beam steering is scheduled for FY 1991. A hybrid photonic–electronic adaptive phased array processor, capable of modifying its operation in response to changing jamming and EW environments, is scheduled for demonstration in FY 1992. An antenna null steering processor will be developed in FY 1993. Demonstrations of optically–controlled phased array systems are scheduled through FY 1997.
- The improvements in quieting of Soviet submarines have necessitated improvements in acoustic detection equipment. Beam–forming for adaptive towed arrays and for all–optical towed arrays will be demonstrated in FY 1991. Experimental multidimensional array configurations will be tested in FY 1992. Additional demonstrations will occur in FY 1994.

d. Algorithm Development

(1) Objectives

Automatic Target Recognition (ATR) algorithm development is concentrating on processing more complex signals from multiple sources simultaneously in a dynamic environment.

(2) Development Milestones

- In FY 1991 various ATR algorithms for smart weapons will be completed or demonstrated. However, true ATR–capable fire–and–forget weapons and sensor systems (e.g., radar, sonar) will not be fielded until the end of the century. In the interim, by FY 1995, Automatic Target Cueing algorithms should be incorporated into fire–and–forget weapons.
- Automatic Target Recognition algorithms have been developed for infrared search and track (IRST) systems which scan for aircraft. Algorithms utilizing spatial temporal techniques are scheduled to be demonstrated in FY 1992.
- Model–based signal processing algorithms compare observed and predicted target signatures based upon an understanding of target phenomenology. Planned demonstrations using model–based vision algorithms include an airborne parallel processor–based SAR to detect ground targets and a carbon dioxide laser radar to detect camouflaged and concealed tactical targets.
- DoD's image processing language (image algebra) attempts to provide a mathematical foundation for digital image processing operations

which would standardize algorithm notation, and to demonstrate algorithm optimization techniques. The DARPA/National Institute of Standards and Technology Princeton Engine project was recently initiated. This work will provide measurement support for image signal processing, and will strive to improve video signal compression processes, enhance image generation/reproduction, and promote improved image transmission capabilities.

- Other ongoing algorithm development efforts applied to a prototype image interpretation system will be used to exploit imagery from reconnaissance systems. Additional algorithms being developed concurrently concentrate on incorporating model-based information, such as tactics, terrain, doctrine, and battlefield limitations to help deduce the existence of enemy targets from SAR, EO, and IR imagery. Algorithm development to provide three-dimensional imagery from two-dimensional imagery sources is being optimized. Work is continuing on optimizing ground level imagery from topographic and high altitude imagery sources.

- Wavelet technology is now being incorporated into the LONG BOW missile for evaluation as a way to enhance optical processing by an order of magnitude over the Fast Fourier Transform. Wavelets have also been used to attain 80:1 compression of audio to increase the storage capacity of solid-state memories for audio recording by that same factor and 10:1 compression of video to result in vastly increased effective data rates for transmission. The exploration of wavelet technology for use in spread spectrum communications is just beginning with the first results due in mid FY 1992

2. Technology Objectives

Technology Objectives — Signal and Image Processing

Technical Area	By 1996	By 2001	By 2006
Algorithms	• Advanced real-time model-based approaches combined with statistical techniques • Model-based algorithms, high-fidelity target models • Increased feedback • Improved scene context • Improved robustness to environment • Effect of atmosphere and ocean	• Supervised and adaptive nonsupervised hardwired neural network algorithms • Enhanced multi-level sensor fusion • Complex scene understanding	• Advanced perception algorithms • Adaptive environmental response capability
Model development	• High-fidelity target, low-fidelity background models for radar, electro-optical imaging sensors • Performance extrapolation to different environments	• High-fidelity target, background, atmosphere, and sensor models for complete system prediction analysis • Mitigation or adaption to environment	• Addition of high countermeasures environment capability
Applications	• Signal processing for airborne, multi-mode conformal array • Full spectrum acoustic signal analysis	• Signal processing for airborne, multi-function systems • Signal processing for long-range active sonar	• Smart skins technology aircraft • Signal processing for large-aperture, high-gain passive acoustic array

3. Resources

Total S&T funding[9] for this critical technology is given in the following table.

Funding — Signal and Image Processing ($M)

FY87–91	FY92	FY93	FY94	FY95	FY96	FY97
753	235	230	232	234	240	219

4. Utilizing the Technology

DoD signal processing research and development is focused on important generic application areas, such as

- Detection, localization, and classification
- Target tracking
- Multi-sensor correlation/fusion
- Adaptive antenna nulling/beam-forming
- Noise reduction
- Diagnostics (turbine engine reliability)
- Speech recognition
- Optical implementation of algorithms
- Smart skin technology
- Adaptive navigation
- Mapping and charting geodesy.

Several strategic defense programs will have to address high-throughput signal processing in a hostile nuclear environment. The sensitivity of focal plane arrays (FPAs) to nuclear particle debris will require complex algorithms to compensate for excitations of detectors from this nuclear debris, which appear later in the processing flow as false targets. Because of the great number of detectors on the FPA, and the very high rate at which these detectors are sampled, enormous amounts of data must be processed to compensate for false targets from nuclear debris. Advanced monolithic wafer-scale integration technology promises the capability to efficiently combine high throughput and memory on a single wafer, allowing the implementation of the algorithms necessary for removing false targets induced by nuclear debris, while minimizing power consumption.

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[9] Funding is derived from programs in the DoD budget. Most programs involve several technologies. It, therefore, becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

The most important signal processing applications depend on advanced high-speed, high-throughput processors. Most of the future DoD signal processing needs will be implemented using current microelectronics technology or through the evolution of photonics technology. Some special manufacturing requirements will exist for the development of analog logic device and memory technology, which can be accomplished by modification of present digital electronics manufacturing techniques.

Phased array technology is on the edge of emerging into the manufacturing arena. Manufacturing issues are heavily dependent on the health of the commercial sector, and include maintaining strong and innovative computer hardware and software industries and ensuring rapid access to the latest in integrated circuit technology. In DoD's manufacturing technology program, a limited number of projects are in place to investigate the manufacturing cost and producibility of transmit/receiver modules. Emphasis is on statistical process control, modeling and simulation, automation equipment technologies, and factory system integration.

2. Projected Industrial Capabilities

For 15 years digital signal processors were packaged using surface mount components (commodity memories and individually packaged ASICs) on multi-layer printed wiring boards. This packaging technology is now incapable of implementing the required functionality, and achieving the required clock rates needed by state-of-the-art avionics signal processors. Instead, hybrid wafer scale and later, full wafer scale packages are required. This will require increases in producibility and manufacturability. Thus, investment in automated manufacturing techniques for such packages will be required.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

In signal processing technology, the objectives of the DoD, DoE, and other federal agencies are quite similar. There is interaction in the technology base with CIA, NIH, NIST, NSA, FBI, DEA, Coast Guard, and the Bureau of Alcohol, Tobacco and Firearms. However, signal processor system design, architecture, and algorithms are unique for weapon applications aimed at military-specific target classes.

To date, radar phased-array systems have been too expensive for use in air traffic control systems. The availability of lower cost, solid-state, active array modules, coupled with increasing requirements for higher traffic handling capability can be expected to make phased-array technology an area of greater interest for this application.

NIST has recently initiated a project to develop the measurement support needed by domestic industry and the US government to process and transmit digital information through the acquisition (funded by DARPA) of a state-of-the-art, parallel-processor computer optimized for digital image processing called the Princeton Engine. Electronic hardware and test methods have also been developed for the testing of digital-to-analog (D/A) and analog-to-digital (A/D) converters with up to 18 bits of resolution and sampling rates up to 300 MSample/s. Methods developed here for characterizing waveform records have been incorporated in the IEEE Standard 1057. Several real-time, low-frequency sampling instruments have been developed at NIST for accurately measuring voltage, current, phase, and power. Recent development of a sampling voltage tracker system makes similar measurements in equivalent time on signals up to 300 MHz.

NSF supports research on new methods of high-speed data acquisition, speed compression and recognition, image compression and enhancement, signal detection and demodulation, and the filtering and estimation of signals in a control system environment. Other areas of research on analog and digital signal processing stress the impact of VLSI and address topics such as signal representation, filtering, novel algorithms, special purpose hardware, and real-time computing. The development of special purpose computer architectures for signal processing is also supported.

In addition, research in the mathematical sciences is aimed at understanding and developing a new set of tools, centering in the concept of wavelets, to replace traditional techniques of Fourier transforms. This is providing new and effective methods for feature extraction in signal processing.

2. R&D in the Private Sector

Use of image processing and pattern analysis techniques is becoming widespread in the commercial sector. Industry is also investing heavily in voice/speech recognition. Medical imaging is one example that has important social implications.

University research has been a significant part of the emergence of many important facets of signal processing technology, such as neural networks, many of which are based on years of research at universities. Realizing the importance of the multi-disciplinary nature of neural networks research and the importance of bridging the gap between neurobiology and the engineering sciences, many universities have started a new curriculum on computational neuroscience. These basic science research efforts will undoubtedly lead to useful new neural network architectures and hardware implementations. Recently, university researchers have begun investigating the potential for wavelets in signal processing applications. DoD is sponsoring substantial university programs to take advantage of the potential multi-scale resolution capabilities of wavelets.

Acoustic-array and anti-submarine warfare (ASW) signal processing share a common technology base and were originally derived from marine seismic techniques. Research emerging in the area of geophysical processing may prove to be directly applicable to towed array systems.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

Signal processing technology involves specialized sensors, processors, and algorithms for real-time acquisition, analysis, discrimination, and recognition of specific targets. Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Effective integration of improved sensor elements with intelligent signal processing functions
- Development of empirically validated algorithms

- Application of massively parallel processors and neural networks to signal processing.

The table on the following page provides a summary comparison of the US and other nations for these selected key aspects of this technology. The US enjoys a significant lead over other countries in the area of signal processing and in the development and use of the extensive data bases needed to support this effort. Effective application of the technology has the potential to reveal sensitive information regarding US threat intelligence and the inherent weaknesses of US systems.

While classification of sensitive information may preclude extensive cooperation on specific techniques and systems, much of the work ongoing in NATO, Sweden, and Israel could contribute to the advancement of signal processors and algorithms applicable to ATR.

The high level of independent research and development activity in all aspects of military sensing are indicative of a rapidly advancing capability in signal processing, and in understanding of the underlying target/clutter phenomena. France, Germany, Japan, Sweden, and the UK have advanced programs in radar technology (including phased arrays and terminal active homing for both air and surface targets).

Most of the allied programs evidence a clear appreciation of the requirement for operating in a dense electromagnetic environment (both self-generated and ECM). While specific details are not available because of classification, the stated goals and objectives of allied programs regarding operations in a high noise/interference environment indicate a high level of confidence in their signal processing capabilities.

Specifically in the area of high-speed data conversion (primarily analog-to-digital conversion), European efforts are proceeding in integrated bipolar and CMOS on a single chip (Bi-CMOS) under the ESPRIT program. Bi-CMOS is also the subject of independent efforts in the UK and the Netherlands.

In the area of processing algorithms and techniques, there is widespread activity. Both Germany and the Netherlands are working on techniques for three-dimensional image processing and filtering for estimation.

Ongoing work at the Royal Signals and Radar Establishment, in conjunction with INMOS Ltd, and Oxford University is of interest for the development of massively parallel signal processors for sonar and radar applications. Germany has developed a prototype phased array for air defense applications. France is developing phased array radars for surface-launched air defense and airborne sensors, and have an active program in IR sensors and in active arrays, all of which will be designed to operate in an ECM environment. Japan is reported to be developing its own active array for use on the FSX, including all software development. This will logically include signal processing software.

Interest in neural networks for signal processing has not been limited to the United States; both Japan and the European nations have made commitments to neural network research. Japan has initiated a government-sponsored program to look at the biological origins of neural networks, and firms such as Fujitsu have begun developing "thinking computers" especially for robotic applications. The Netherlands and Germany are exploring neural networks in two- and three-dimensional imaging. The UK has expressed an interest in radar processing applications. The Alvey program has a major effort in adaptive user interfaces that may provide benefit to future neural net applications. Finland and Sweden have research efforts in the use of neurocomputing to pattern recognition. Moreover, the

International Neural Network Society was formed in the spring of 1987 and has grown immensely.

The Soviets are very active in neural network technology, but their efforts are still in the early stages. Much of their research focuses on developing computational models of neurons and the brain. In terms of hardware and VLSI technology, they are trying to implement these neural network architectures, and have reportedly built prototype neural processors and computers.

2. Exchange Agreements

The high level of exchange activity in radar and in passive sensors is reflected in and supported by a high level of exchange in signal processing. The NATO Defense Research Groups (DRG) for Long-Term Scientific Studies and Long-Range Research Related to Air Defense, Optics and Infrared Technologies, and Electronic Warfare Concepts and Technology all will provide a mechanism for some level of exchange of fundamental requirements and scientific information in signal processing. The DRG on Identification of Submarines is directly applicable to passive ASW towed array signal processing.

The Technology Cooperation Program (TTCP) also provides mechanisms for a range of applicable exchange activities. Specific topics under TTCP support information exchange in signal and image processing for IR and electro-optical sensors, undersea acoustic signal processing for ASW, EW signal processing, and radar signal processing.

Each of the Services also has a significant number of exchanges with NATO and other friendly nations in all of the TTCP topics, and additional topics such as passive acoustic and seismic detection for ground systems and counter-intrusion detection. The Service programs also include exchanges in specific application of signal processing technology, such as space-based IR surveillance and airborne ASW acoustics.

Summary Comparison -- Signal and Image Processing

Selected Elements	USSR	NATO Allies	Japan	Others
Effective integration of improved sensor elements with intelligent signal processing functions	□	□□	□□	□□ Sweden, Israel
Development of empirically validated algorithms	□□□□ ○	□□	□	
Application of massively parallel processors and neural networks to signal processing	□	□□	□□□□ ○	
Overall[d]	□□	□□ [a]	□□ [b]	□□ [c] Sweden, Israel

[a] While not predominant in any key aspect of this technology, the UK and France have specific capabilities of interest.

[b] In comparison to the United States, Japan has limited experience in fielding operational phased-array radars. Their experience in photonics and high-speed digital processing can make a significant contribution to the US development of advanced signal processing

[c] The sensitive nature of a single processing technology may limit cooperative opportunities; however, technologies could contribute to critical component developments.

[d] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□	broad technical achievement; allies capable of major contributions
□□□	moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
□□	generally lagging; allies may be capable of contributing in selected areas
□	lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators -- where significant or important capabilities exist (i.e., 3 or 4 blocks):

+	Foreign capability increasing at a faster rate than the United States
○	Foreign capability increasing at a similar rate to the United States
—	Foreign capability increasing at a slower rate than the United States

10. SIGNATURE CONTROL

10. SIGNATURE CONTROL

A. DESCRIPTION OF TECHNOLOGY

This critical technology enables the modification of signatures emanating from weapon systems, in order to reduce their detectability or disguise their source, by altering those characteristics by which systems may be detected, recognized, and engaged. They include radar, infrared, visual, acoustic, and magnetic signatures, among others, of aerospace vehicles, military land vehicles, and naval ships and submarines. Some signatures result from emissions (radio, thermal, acoustic, or other) from the vehicle, and other signatures occur when natural or manmade energy is reflected by the vehicle, so that the vehicle contrasts with its background.

The reduction or control of vehicle signatures greatly improves survivability, resulting in improved weapons effectiveness. In some scenarios, the objective is not signature reduction, but rather signature enhancement, typically for deception or misdirection against hostile radars or ESM (electronic support measures) systems. The reduction of radar signatures is accomplished by vehicle shaping, the use of radar absorbing materials to reduce radar echoes (mostly at microwave frequencies), and passive or active cancellation techniques. The reduction of infrared signature is accomplished by cooling or heating, and by applying special materia. for background matching to reduce detection by passive systems. For example the visual outline of a tank might be modified with a camouflage net. The acoustic target strength of submarines can be reduced by structural shaping and application of anechoic coatings. An understanding of structural acoustics and the conversion of vibrational energy induced by machinery, hydrodynamic flow, or impinging active sonar pulses is key to passive and active acoustic signature control as well as decoy design and discrimination. Radiated noise from hull and machinery is controlled by structural acoustics and fluid dynamic design. The technology (materials, structural acoustics, and fluid dynamics) to reduce hull, machinery, and weapon system noise is essential to maintaining US undersea warfare superiority The reduction of magnetic signature is accomplished by deperming and degaussing of the hull and machinery of surface ships, submarines, and tanks. The understanding and control of permanent and induced magnetism and of electric fields is essential to countering the effects of magnetic mines.

As a critical adjunct to platform signature reduction, the signatures possessed by specific weapons and by installed systems must also be reduced. For example, rocket plume reduction is an important part of weapon signature reduction efforts. Vehicles produce wakes in moving through water and air. These wakes can be detected visually, by radar, by passive infrared, and other detectors. As the hard body signatures of vehicles are reduced, the importance of minimizing their wakes will increase. Reduction of the detectability of wakes will require a better understanding of the exact features of the wake that are being detected by sensors, careful design, and possibly changes in the propulsors of ships and craft, and other vehicles.

Sometimes the objective is not signature reduction but rather signature control, typically for deception. Decoy vehicles should reasonably mimic the signature characteristics of actual weapon systems, including signature fluctuations and scintillation rates. As threat sensor capabilities improve, there will be a requirement to mimic the signature information that can be extracted via signal processing techniques, such as image enhancement. In some cases, decoy signatures must be increased rather than reduced, for example, to increase the radar cross section of a small decoy until it looks like a ship on a radar screen. Similarly, it may be desirable to displace the magnetic signature of tanks, for example, to cause fuze actuation at safe distances.

The capability to control communication emissions through low probability of intercept (LPI) techniques, among others, is crucial to a wide range of operations, from low intensity to full-scale conflicts.

Technology Sets in Signature Control

- Radar signature (radar cross section) reduction
- Infrared, visual, and ultraviolet signature reduction and management
- Acoustic quieting
- Low probability of intercept radars, communications, and navigation (electronic emission control)
- Deceptive signatures (emissions and decoys)
- Magnetic silencing

B. PAYOFF

1. Impact on Future Weapon Systems

a. Weapon System Performance

Reduction of the signatures of weapon systems significantly affects their general design, support, and effectiveness. The utilization of signature reduction techniques can improve the penetration capability of strategic systems and the survivability and effectiveness of tactical systems. The use of signature reduction technology for strategic systems can render an adversary's early warning radar network less effective, thus allowing greater penetration, reduced weapon system losses, and flight plans at higher altitudes, thereby improving the capability to find and destroy targets. The reduction of the signature of tactical systems (such as air-to-air interceptors and air-to-ground attack aircraft) allows those aircraft to achieve higher exchange ratios and improved survivability. The reduction of both radar and infrared signature diminishes the threat from surface-to-air missiles, thus enabling the destruction of highly protected targets without serious loss of aircraft. Similarly, the reduction of both radar and infrared signature diminishes the threat of air strike munitions to ground vehicles and naval vessels. The deployment of decoys with proper signature and discriminant control can saturate missile and air defense networks or air strike capability, thereby minimizing the loss of re-entry systems, aircraft, ground vehicles, and naval vessels by forcing an opponent into the wasteful expenditure of munitions. Technologies for acoustic and magnetic signature control can enhance US undersea warfare superiority. The reduction of magnetic signatures can support minefield penetration by submarines with reduced risk. The threat from other weapons such as missiles and mass scatterable mines, most of which employ magnetic fuzing, will be greatly reduced.

As the stealthiness of missile airframes and platforms increases, missile exhaust plume signature plays a greater role in early detection. Lower visibility plumes will minimize detection of both the launching platform and the attacking missile and thereby enhance battlefield survivability. If critical launch platforms (aircraft, ships, tanks, personnel) are to be protected, then the plumes from rocket motors must be made far less visible.

An essential point is that "stealth" and higher performance sensor technology can be expected to spread to other countries especially if the first steps are relatively low cost. To maintain affordable combat loss/exchange ratios, we must be significantly better at signature control than our potential opponents will be. There is a need to retrofit and upgrade older systems until they are replaced with new vehicles/platforms.

b. Weapon Systems Logistics

Exotic shapes and new advanced signature control materials will adversely influence systems maintenance and supportability, if logistics concerns are not addressed during the design process. Critical areas of impact include new and specialized handling equipment, alternate access provisions, totally new repair and rework needs, new inspection and diagnostic requirements, and new maintenance skills.

A system that meets future signature control needs, yet is not easily serviceable over the range of normal anticipated sustaining support needs will not be effective under operational conditions.

New systems incorporating signature control technologies must undergo extensive simulation and modeling from a logistics perspective. There must be a disciplined approach that balances the operational performance needs with the logistics sustaining support requirements. The technical challenges to develop and implement logistically supportable systems incorporating signature control technologies exceed those of simply developing signature control materials and shapes.

2. Potential Benefits to Industrial Base

a. Manufacturing Infrastructure

Signature control is primarily a military need, and the industrial base will be largely dependent on government funding. Few significant commercial applications exist. One counter-example is the covering of structures in crowded urban environments with TV-absorbing materials to reduce TV echoes. Others include packaging of microwavable foods, and industrial and medical microwave instrumentation systems. TV-absorbing materials have been used in Japan but not in the United States. At least one US firm markets a radar-absorbing cover for automobile front ends; radar-absorbing materials are also used in the construction of commercial radars. Acoustic quieting through structural vibration isolation and absorption is widely applied to control noise pollution in modern industrial factories and urban office buildings.

The measurement technology developed for signature control finds application in other fields. Techniques for electronic emission control may find application as security enhancements in banks and other financial institutions.

b. Logistics Infrastructure

Signature control technology development must consider and address the technical needs of the DoD support industrial base.

Although the DoD depot environments may anticipate few benefits from signature control technologies, these depots will need new testing and health monitoring approaches to provide life cycle sustaining support. Prognostic algorithms and approaches will be needed to project long-term depot induction needs for technologies that lack historical operational experience. Since this technology area falls primarily within military needs, there is little opportunity for the DoD to leverage off the commercial industrial base benefits.

C. S&T PROGRAMS

Detail program descriptions and technology objectives are classified

3. Resources

Funding information for this critical technology comes from unclassified sources only.

Funding — Signature Control ($M)

FY87-91	FY92	FY93	FY94	FY95	FY96	FY97
572	109	102	89	87	86	88

4. Utilizing the Technology

Signature control technologies presently implemented or under development are broadly transitionable to all new aircraft, ships, and ground vehicles. In addition, there is retrofit potential for RAM/RAS, coatings and paints, acoustic materials, cancellation, apertures and sensors, propellants and plume additives, navigation equipment, countermeasures equipment, and quiet propulsors.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

Industrial process technologies which are critical to advanced signature control concepts for ships and submarines include computer-aided design and computer-aided manufacturing (CAD/CAM), computer-numerical control (CNC) machine tools, laser and optical hardware, and robotics. These technologies are important to propulsor and machine quieting.

High temperature, high current superconductors of reasonable size, weight, and cost will be necessary to support high-level deperming of entire ships and submarines. Until they become available, high-level deperm is practical only for major machinery components prior to installation.

1. Current Manufacturing Capabilities

Domestic manufacturing capabilities that support machinery silencing are primarily in the areas of machining, casting, and molding. Other industrial concerns provide for manufacture of noise attenuation components and treatments. This industrial base, in addition to the shipyards and Navy laboratories, provides the quiet components and materials for machinery silencing.

The control of the acoustic signature associated with the propulsor of a marine vehicle requires CNC machines to provide a more repeatable surface contour. Domestic centers that have a capability to manufacture large-scale submarine and surface ship propulsors are starting to employ CNC machines. Trade-offs are being made between the costs of machines, hand-finishing, programming, and the degree of signature control. Welding of a propulsor will usually lead to significant variations from the specified contour because of the excessive heat that must be applied. The use of lightweight composite materials for submarine shafts and propulsors represents the introduction of an entirely new class of manufacturing technologies.

Manufacturing capabilities exist among DoD weapon systems contractors and selected specialty materials manufacturers to support applications of current technology to aviation systems.

The industries for gas turbine power plants, heat exchangers, and gas scrubbing support the reduction of signatures from exhaust gases.

2. Projected Manufacturing Capabilities

New and improved manufacturing capabilities will be required to transfer new signature technology materials to general system applications that emphasize producibility, cost, and performance. Additional effort will be required to achieve close tolerance manufacturing and to develop adequate capability to remanufacture or repair DoD systems in the inventory.

For silencing ship machinery, expanded, cost-effective capability in precision three dimensional machining is required. Increased capability in fabricating components from advanced materials, such as titanium, is required.

Silencing of ship propulsors requires that distortion due to welding, and surface contour variations due to hand finishing, be eliminated. This will be accomplished by incorporation of laser welding; its rapid moving, localized heat source minimizes heat induced stresses. Multiple-axis CNC machines with computer processing will also be used to permit a complete machined definition of the blade surfaces. This will be accomplished with improved surface definition by software and the integration of this software into a standard CAD system. Precision measurements of the blade surfaces and their position will be accomplished using a laser/robotics inspection system. The combination of these three advanced capabilities will provide a complete manufacturing work cell.

Current techniques of magna-fluxing to verify the integrity of welds imparts large magnetic signatures to hardened steel machinery components. High-level deperming of individual components prior to ship installation will be required until such time as the availability of superconducting cables to provide current levels which are necesary for the deperming of entire ship platforms in a single operation

Additional manufacturing capabilities will be required for the reduction of acoustic signatures of surface ships. There will be a requirement to make and securely apply acoustic coatings and to manufacture retractable air systems that can be used to create an air bubble screen around the hulls and propulsors of the ships.

The precise application of coatings for radar absorption and acoustic isolation can be effected through the use of robotics. Quality control inspections throughout the course of the application can also be accomplished through robotic techniques. Similar techniques may be applicable to the application of IR and visual signature control coatings.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

This is predominantly a DoD technology which is not of general interest to other government agencies.

2. R&D in the Private Sector

DoD-sponsored university research efforts involving signature control technology include work in multi-functional polymers (with superior mechanical integrity in severe environments), ultra-structured ceramics materials design (with tailored IR signature absorption), and synthesis of macromolecular ceramic materials (for ultraviolet and visible wavelength sensor protection). Improvement of supercomputational capability for fluid dynamics and electromagnetic solutions (both techniques and computational speed) are aggressively pursued in private industry and should be strongly encouraged in colleges and universities. Aggressive pursuit of advanced image and signal processing capability should also be aggressively encouraged in colleges and universities.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

While the United States is the recognized leader in developing signature-related expertise, the interest and technology available from other countries, most notably our NATO allies and Japan, continues to advance. While the details of implementation and actual levels of signature reduction achieved continue to be highly classified, the general principles behind much of Stealth technology are becoming well understood.

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Improved modeling and measurement of broadband scattering characteristics of complex shapes.
- Structural radar-absorbing material (RAM) components and ferrite/polymer composites.
- IR signature reduction (including propellants and plume).
- Acoustic signature reduction in marine platforms and techniques for dynamic balancing of complex rotating machinery.
- Helicopter acoustic signature reduction.

The table on the following page provides a summary overview of foreign capability in these aspects of the technology.

The United States is the leader in developing low-signature propellants and has international formal data exchange agreements. The Services are attempting to reduce the visible, infrared, ultraviolet, and radar signatures of tactical missile motors. A four-powers agreement exists between the United States, the UK, the FRG, and France to develop high-energy, low-sensitivity, low-signature propellant technology.

The United States relies upon several countries for certain rocket propellant ingredients and other propellant development activities. However, the United States does not rely substantially upon others for research, manpower, or manufacturing processes related to low observability. While cooperative arrangements exist externally, the United States retains the capabilities to move ahead in this area.

Classification restricts access by foreign countries to information related to signature control. Generic RAM, however, are available to foreign enterprises. In fact, one of the largest RAM manufacturers in this country is foreign owned. One of the enhanced materials developed initially by the parent company is reported to have good broadband electrical properties and may be a candidate for use on a future European fighter aircraft.

A promising area for cooperative research is the tailoring of composite materials to attain specific radio frequency characteristics, such as Japan's technology in conventional carbon fiber reinforced and advanced ceramics and promising research in Israel on techniques using carbon fiber.

Summary Comparison — Signature Control

Selected Elements	USSR	NATO Allies	Japan	Others
Improved modeling and measurement of broadband scattering characteristics of complex shapes	□□	□□	□□	
Structural RAM components and ferrites/polymer composites	□	□□	□□□ O	□□ Israel
IR signature reduction, (propellants and plume)	□□	□□	□□	
Acoustic signature reduction in marine platforms plus, techniques for dynamic balancing of complex rotating machinery	□□	□□	□	□ Israel
Helicopter acoustic signature reduction	□□□ O	□□□ –	□	
Overall[a]	□□	□□	□□	

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□	broad technical achievement; allies capable of major contributions
□□□	moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
□□	generally lagging; allies may be capable of contributing in selected areas
□	lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators – where significant or important capabilities exist (i.e., 3 or 4 blocks):

+	Foreign capability increasing at a faster rate than the United States
O	Foreign capability increasing at a similar rate to the United States
–	Foreign capability increasing at a slower rate than the United States

2. Exchange Agreements

Because of the high level of classification, few specific agreements could be identified for this area.

11. WEAPON SYSTEM ENVIRONMENT

11. WEAPON SYSTEM ENVIRONMENT

A. DESCRIPTION OF TECHNOLOGY

Due to the increasing sensitivity of each generation of weapon system sensors, DoD systems and tactical operations are increasingly influenced by natural environmental conditions (e.g., weather, seasons, terrain). The limitations and potential leverage of environmental factors must be clearly understood to increase existing system capabilities and performance and to optimize the design of new systems. Specific technological elements include wide area and high-resolution remote sensors, data acquisition systems, analysis and predictive numerical codes, tactical environmental data processing, and decision aids developed from environment-system effects analyses.

Weapon system environment technology differs from other critical technologies in that it does not develop specific hardware. It is included because it is critical in the selection, development, and operation of superior weapon systems, for such missions as anti-submarine warfare (ASW), battlefield surveillance, and communications.

Technology Sets in Weapon System Environment

- Ocean characterization and prediction
- Environmental characterization and prediction for local target area conditions
- Target environment analysis and scene characterization

B. PAYOFF

1. Impact on Future Weapon Systems

The weapon system environment will become more crucial due to three factors:

- The next conflict may not be one of attrition; success of the first engagement may be critical to the outcome.
- Countering quiet submarines and low-signature aircraft and missiles demands fine-grained environmental data.
- Low-intensity conflicts increase the need for real-time environmental data.

Simulations have indicated that by using proper environmental data, the theoretical probability of acoustic detection of submarines can be increased by 30 to 40 percent; the range of the first detection extended by 20 to 80 percent; and the duration for which a contact is held lengthened by 20 to 40 percent. Improvements of this magnitude are crucial to counter adversary submarine quieting and regain the ASW advantage once enjoyed by US forces.

Current smart weapons (SW) systems have high false alarm rates when tested in a variety of environmental conditions. Integration of comprehensive environmental knowledge into the logic modules, design, and testing and evaluation of these systems can dramatically reduce false alarms and increase their effectiveness.

Electro-magnetic fluctuations in the ionosphere degrade over-the-horizon (OTH) radar range and azimuth performance, and can especially degrade the capability to detect low–observable targets at night. Modifying the ionosphere to create regions of enhanced ionization may enhance overall radar performance, day and night; permit surveillance and target acquisition at closer, possibly tactical, ranges; enable high–resolution detection and tracking of very small radar cross–section targets; and improve communications. Magnetic ASW and minehunting sensors, spaceborne systems, and communications performance are also adversely affected by ionospheric disturbances. The development of predictive ionospheric models will enhance OTH frequency management for maximum effectiveness, help protect spaceborne systems, and permit maximum effectiveness of magnetic sensor systems.

Targeting and mission planning, including the choice of weapons and tactics, depend largely on the tactical environment in which they will be used. High–resolution weather prediction techniques and algorithms known as electro–optical tactical decision aids (EOTDAs) are being developed to assess probable target signatures, background signatures, and atmospheric effects. The products available to the tactical commander will assist in proper selection of weapons and tactics for the given target and the expected environmental conditions.

Testing has shown that current imaging and detection systems are not optimized for atmospheric conditions. Using knowledge of environmental effects, researchers have, through selective filtering, optimized the performance of infrared (IR) sensors to provide an order of magnitude increase in the signal–to–noise ratio of currently fielded IR systems. In addition, understanding the effects of atmospheric conditions on terrain propagation of seismo–acoustic signals will enhance the performance of ground–based seismo–acoustic sensors for weapons targeting and passive battlefield surveillance. Knowledge of the nature of ionospheric effects on satellite and ground–based radar sensors has also dramatically increased our confidence in extrapolating to the extremes of a nuclear conflict.

2. Potential Benefits To The Industrial Base

The industrial base of the United States will enjoy a variety of benefits from research in this area. Examples include marine and atmospheric weather prediction for disaster warning, optimal aircraft and ship routing, and the use of knowledge of the sea for predicting optimal fishing locations. Remote sensing of the environment will provide insights into crop optimization. Improved remote detection and weather prediction capabilities will provide advanced warning of danger over land areas and at sea. Improved coastal oceanographic and meteorological knowledge will directly affect coastal and harbor construction designs. The accurate prediction of coastal phenomena will benefit the coastal construction and recreation industries as well as improving production of pollutant and oil spill dispersal.

Goals and Payoffs -- Weapon System Environment

Application	Goal	Payoff
Oceanography	• Predict global and mesoscale ocean circulation • Predict marginal ice zone movement, behavior, and boundaries • Understand dependence of small-scale oceanography on larger-scale properties	• Tactical support of employment of surveillance assets and weapons • Improved support to search, rescue, and salvage operations • Improve localization for weapon systems
Underwater acoustics	• Describe and predict acoustic propagation in shallow and deep water environments • Improve performance prediction of bottom-mounted sensors • Model under-ice acoustic interaction	• Passive range and depth localization combined with detection • Broadband acoustics signal processing to offset narrowband quieting • Improved localization of under-ice targets • Reduced false targets
Meteorology	• Accurately forecast global, regional, and local weather (7 to 10 days, 3 to 5 days, and 24 hours, respectively) • Describe and predict atmospheric boundary layer (surface to 1,000 m) phenomena • Improve tropical cyclone forecasting • Understand and mitigate environmental effects on weapons systems	• Improved performance of surveillance and C3 systems (electro-magnetic and electro-optical) • Incorporation of real-time environmental effects into battle management and system operation • Tactical ship and aircraft routings, reduced damage to ships and cargo, fuel savings, covert movement of forces • More effective weapons systems development, deployment, and decision aids for the operational commander
Remote sensing	• Provide real-time quantitative data worldwide • Supplement observing networks in data-sparse and data-denied areas • Provide boundary data on marginal ice zone • Locate and identify major ocean features and weather systems • Develop sensing techniques extending environmental parameter coverage	• Rapid mapping of regions of interest • Improved initialization of prediction models for forecasting • Sensing capability over remote areas • Tactical support to battle management and weapons employment • Enhancement of weapon system design and testing
Ionosphere	• Describe and predict ionospheric disturbances and hazards • Develop modification techniques	• Protection of space assets • Enhance performance of over-the-horizon radar • Enhance communications

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Ocean Characterization and Prediction

(1) Objectives

Ocean circulation and structure models, although progressing rapidly, are heavily dependent on sparse surface and undersea data sources. High horizontal resolution, eddy resolving ocean circulation models are being coupled to ocean basin and high-resolution, mixed-layer models to resolve the ocean with sufficient detail for improved performance prediction of acoustic ASW systems. Future improvements include the coupling of the atmosphere with the ocean mixed layer through the addition of a marine boundary layer model, which will include two-way feedback between the ocean and the atmosphere. Acoustic tomography and other advanced in situ oceanographic measurements will help provide real-time input for the predictive models and for developing a tactical oceanographic data base. New techniques in data acquisition from various sources and for data assimilation into the numerical models are required if the predictive systems are to perform acceptably.

Underwater acoustics drives much of the ocean modeling effort with the objective of supporting the successful development and use of ASW surveillance systems, ASW weapons systems, and ASW countermeasures. Technology goals are directed to more effectively detect, localize, and track high-performance threat submarines. Thrust areas of this technology include active sensor systems, arctic systems, and seismic sensors. Bottom-scattering and reverberation models are the primary acoustic propagation elements of the active system, supporting both the battle group multi-static sonar system and the low-frequency active acoustic system. Determination of high-resolution directional ocean noise properties is essential to the performance of planned high-resolution active and passive sonar systems. New spatial and temporal statistical measures support the new acoustic system development efforts as well as operations strategy. Remote sensing of oceanographic data is essential to improve the extremely sparse data set and to improve models through process oriented observations designed to elucidate processes not adequately modeled. Efforts will focus on developing the concept of integrated synergistic systems for environmental measurements with global coverage from space, air, surface, and underwater-based sensors.

(2) Development Milestones

- Large-scale ocean prediction capability
  - North Atlantic Basin Model (FY 1992)
  - Western Mediterranean Model (FY 1993)
  - Air-Ice Coupled Model (FY 1995)
  - Global Ocean Prediction Data-driven models (FY 1996)
  - Marine Boundary Layer Coupling (FY 1997)
- Tactical ocean area acoustic propagation models
  - North Atlantic (FY 1992)
  - Mixed layer (FY 1993)
  - Shallow water (FY 1994)

- Shipboard predictive capability (FY 1995)
- Analytic models for non-acoustic ASW technologies (FY 1997)

- Ocean in situ and remote sensing capabilities
  - Millimeter wave humidity sounder (FY 1993)
  - Basin Temperature Measurement System (FY 1994)
  - Microwave wind stress algorithms (FY 1994)
  - Prototype Ocean Observation System Instruments (FY 1994)
  - Millimeter wave imager/sounder (FY 1995)
  - Multibeam altimeter measurements of ocean surface slope vector (FY 1996)
  - Integrated ocean observation system (FY 1998)

b. Environmental Characterization and Prediction for Local (Target) Area Conditions

(1) Objectives

The physical processes governing mesoscale atmospheric (500 to 800 km) dynamics are, in general, known well enough for the serious pursuit of predictive systems to support tactical decisions regarding weapon systems employment. Recent modeling of atmospheric processes at battlefield scales is demonstrating that computational power is nearly available, that numerical techniques are improving rapidly, and that data requirements for the predictive models may be achievable. High-resolution tactical atmospheric models will be developed to integrate locally acquired battlefield data with regional or global data to support the tactical commander with definitive 3- to 48-hour forecasts for weather conditions in the tactical area of interest. High-resolution predictions for rainfall and electro-optical/infrared (EO/IR) propagation, for instance, will be coupled directly with terrain models to generate mobility predictions for tactical planning and EO/IR target signature and background predictions for weapons selection.

Current remote sensing efforts are focused on understanding the variation of individual environmental parameters such as winds, temperature, and moisture; using active sensors such as lidar and radar; and passive sensors such as infrared. Future efforts will focus on developing the concept of integrated, synergistic systems for environmental measurements with global coverage from both surface and space-based platforms. The use of multiple sensors in weapon systems requires quantifiable knowledge of the limitations imposed by environmental effects.

(2) Development Milestones

- Battlefield scale environmental prediction capability
  - Atmospheric effects simulator (FY 1992)
  - Multisensor data fusion (FY 1993)
  - Real time cloud forecasting (FY 1994)

- Automated six-hour tactical forecasting capability (FY 1995)
- Tactical forecasting system (FY 1997)

- Remote sensing technology for atmospheric and terrain specification
  - Real time data retrieval (FY 1992)
  - Multispectral temperature retrievals (FY 1993)
  - Stand-off fluorescent lidar remote detection (FY 1993)
  - Multispectral cloud specification (FY 1994)
  - Passive/covert vertical wind sensor (FY 1995)
  - Multispectral humidity sounder (FY 1996)
  - Space lidar experiment (FY 1997)
  - Automated atmospheric profiler for Artillery Met (FY 1997)
- Ionospheric specification for enhanced surveillance
  - Semi-empirical specification model (FY 1992)
  - Ionospheric heater initial operations (FY 1993)
  - Ionospheric storm specification capability (FY 1994)
  - Demonstrate UV ionospheric mapper (FY 1995)
  - Ionospheric-neutral coupling model (FY 1996)

c. Target Environment Analysis and Scene Generation

(1) Objectives

Measuring and modeling the dynamic electro-magnetic (EM) and seismic/ acoustic character of terrain and the atmospheric boundary layer are leading to realistically simulated evaluations of conceptual and prototype smart weapon/automatic target recognition (SW/ATR) systems. Simulation allows early consideration of a variety of operational conditions in weapon design as well as optimization of test and evaluation efforts and the translation of sparse test data to a variety of other conditions and scenarios. The Balanced Technology Initiative (BTI) program on smart weapons operability enhancement is the integrating force for DoD technology base efforts to consider systematic incorporation of the environment into the research, development, test, and evaluation process for SW/ATR devices. The SDIO program is conducting measurements of target backgrounds for a number of strategic scenarios.

(2) Development Milestones

- Strategic scene generation technology
  - SDI Target background measurements (FY 1991)
  - SDI Strategic scene generator (FY 1992)

- Midcourse background specification (FY 1995)
- Celestial IR backgrounds (FY 1996)
- SDI background clutter scene generator (FY 1997)

- Tactical scene generation technology
  - Environment-systems performance interactions (FY 1991)
  - IR scene codes (FY 1992)
  - Millimeter wave scene codes (FY 1993)
  - Interactive scene visualization models of battlefield atmospheres (FY 1994)
  - Multisensor scene generation (FY 1995)
  - ATR scene metrics specification (FY 1997)
- Electro-optical/IR/millimeter wave propagation codes
  - MODTRAN code (FY 1991)
  - Optical turbulence compensation (FY 1992)
  - LOWTRAN maritime aerosol model (FY 1993)
  - Forecasting capability of atmospheric structure effects (FY 1997)

2. Technology Objectives

Technology Objectives — Weapon System Environment

Application	By 1997	By 2002	By 2007
Oceanographic specification and prediction for acoustic propagation	• Global predictions of ocean circulation • Regional predictions of mixed layer • Range dependent 3-D acoustic models with emphasis on broadband low-frequency propagation	• Basin-scale eddy-resolving ocean specification and acoustic prediction	• Global ocean prediction and acoustic surveillance
Environmental specification and prediction for local (target) area conditions	• Automated tactical forecast capability • Multispectral remote sensing systems • Ionospheric-neutral coupling model	• 24-hour high-resolution battlefield forecast capability • Enhanced OTH surveillance capability	• Enhanced low observable detection • 48-72 hour battlefield environment prediction
Target environment analysis and scene specification	• Strategic scene generator to include background clutter • ATR scene metrics specification • Atmospheric structure effects prediction capability	• Strategic system applications packages • ATR DT&E/mission planning via environmentally driven synthetic scene generation	• Autonomous systems design criteria • Integrated millimeter wave scene generation

3. Resources

Total S&T funding[10] for this critical technology is given in the table below.

Funding — Weapon Systems Environment ($M)

FY87-91	FY92	FY93	FY94	FY95	FY96	FY97
929	232	238	246	249	252	260

4. Utilizing the Technology

This critical technology relates to virtually all aspects of DoD investment strategy in that all weapon systems and military operations depend on the environment in which they operate. This fact has been demonstrated repeatedly in systems development and in the adverse effects suffered by fielded systems inadequately designed for the tactical environment.

Major programs utilizing oceanographic data include

- ASW environmental acoustic support program for providing improved operational and design data for long- and short-range acoustic surveillance systems;
- Acoustic performance prediction program using ocean forecast models to improve fleet ASW acoustic prediction capabilities;
- Air-ocean prediction program for providing improved data for weather forecasting at sea by incorporating air-sea interactions;
- Fleet air-ocean equipment program directed toward improved data collection and dissemination equipment; and
- Tactical environmental support system program for upgrading single-station forecast capabilities by improved fusion of local data with forecast model inputs from central facilities.

Major developmental Navy ASW systems supported by these efforts include the high-gain sonar array and the low-frequency active sonar programs.

Major programs utilizing atmospheric, space, and terrain data include the suite of SW/ATR devices being developed in the Army and Air Force (a nearly $100 million near-term investment) and the Strategic Defense Initiative Office (SDIO) Phase I systems. Devices such as the search and destroy armor (SADARM) munition, wide-area mines (WAM), and sensor-fuzed weapons (SFW) demand critical knowledge of the environment to be effective, as has been demonstrated in recent tests. Consideration of the environment early in the design stages and the ability to optimize and translate test results are critical to attaining multi-sensor fusion and autonomous decision-making capabilities.

The tactical employment of JOINT STARS is directly affected by environmental events. JOINT STARS requires theater-scale forecasts of precipitation intensity and duration

[10] Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

in target areas and forecasts of atmospheric refraction for anomalous propagation. Tactical battlefield forecasts for JOINT STARS are critical for successful management of offensive and defensive forces because precipitation can reduce signal-to-noise ratios below acceptable limits and interrupt satellite communications links. High-resolution forecasts of precipitation events permits real-time management of system resources and capabilities to minimize the effects of weather.

The Army is developing tactical weather system concepts to support the battlefield commander with special forecasts and decision aids for tactical planning operations and weapons selection. When available, battlefield scale models for 3- to 48-hour forecasts will be integrated to provide the accuracy necessary for detailed next-day planning. The system will be located at different echelons of command and operated by Air Force weather officers and teams.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

The domestic industrial and manufacturing base for weapon system environments is made up of subsidiaries and small divisions of larger diversified corporations, small companies, partnerships, and individual consultants. Estimates place this total industry at about 1,000 small groups (excluding universities) of scientists and technologists working on today's defense and commercial environmental problems. The supporting domestic industrial and manufacturing base includes the operational environmental forecasting industry, instrument design manufacturers, and specialized testing and fabrication facilities. Operational forecasting members are typically ocean transportation companies interested in optimum track ship routing; airlines interested in optimum path aircraft routing; off-shore oil platform operations; and local area or city forecasting firms which provide city managers with predictions of local weather patterns. The field of instrument design and manufacturing includes commercial enterprises which provide equipment for data telemetry, storage and processing; electronic profilers and vertical atmospheric sampling equipment; and instrumentation to measure ocean temperature, color, acoustics, tides, and depth. Specialized testing or fabrication facilities are provided by a small group of firms manufacturing controlled pressure test vehicles, altitude simulation test chambers, and in-tank sea-ice dynamics testing facilities.

Weapon system environment technology relies on the hardware and software manufacturing segments that address computationally complex problems. The continued health of the US computer industr is particularly important. Future military capabilities based on this technology will require a significant number of advanced, high capability computing systems, many of which must be hardened to withstand operational conditions.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

The National Oceanic and Atmospheric Administration has the primary responsibility for observation and dissemination of weather data and forecasts in the United States. This agency also sponsors a prototype regional observing and forecasting system (PROFS), which is attempting to address processes on battlefield scales. Research into atmospheric and oceanographic processes is also conducted under sponsorship of NASA, the Department of Energy, the Environmental Protection Agency, the National Science Foundation (NSF), and the Department of Agriculture (Forest Service). These agencies use in-house and contracted capabilities to achieve their research objectives. NASA and NSF both sponsor research in oceanography followed NASA's remote sensing efforts are followed closely by DoD.

NIST has been responsible for developing environmental prediction, scene models. The model for control architecture has been adopted by NASA, Bureau of Mines, and other governmental agencies including DoD branches. It is unique in that the environment is explicitly contained in a major module called "world model." World Model connects sensory systems to the control/actuator systems of autonomous systems, often vehicles. This model is constantly updated in real time by sensors, especially those using machine vision. Current work focuses on image flow as a means of finding range by passive non-detectable manner.

The NSF supports a number of programs on the remote sensing of atmospheric parameters, focusing on aircraft-based and ground-based measurements. Aircraft measurements include lidar and a variety of cloud micro-physical measurement systems. Ground-based systems emphasize radars and lidars. These observational systems focus on physical processes and are not directed at obtaining the required input data for theater-scale prediction models. NSF's basic research program in mesoscale meteorology focuses on improving the theoretical and numerical (descriptive) models of mesoscale phenomena, developing new instrumentation, supporting field experiments to gather special research data sets, and using the data in diagnostic studies of mesoscale phenomena. In those regards, NSF encourages developing and using mesoscale numerical prediction models as tools to aid in the development of improved understanding of phenomena and complex processes on the mesoscale. While NSF does not support research in weather prediction per se, support for understanding and measuring mesoscale atmospheric processes, dynamics, and numerical methods can contribute to improved NWP models developed by other agencies such as DoD.

2. R&D in the Private Sector

Industry R&D is very limited and primarily related to construction practices and pollution control. It is particularly noteworthy that the ocean and atmospheric technology base in the United States is crucially dependent on federal investment. Available data indicate the IR&D investment in geophysics is less than 5 percent of the Air Force investment, while IR&D investment in electronics is 500 percent of the Air Force's. The limited industrial R&D is a primary reason that environmental R&D is a critical technology for DoD.

The Services pursue this technology under the University Research Initiative and Small Business Innovative Research (SBIR) programs and will continue to do so. The military environment has not been the subject of major IR&D investment because it is not a capability commonly found in US industrial firms.

University research efforts, closely analogous to NSF-sponsored research, also contributes to this technology area through efforts in studying weather forecasting, climatology, ionospheric physics, meteorology, and other atmospheric, oceanographic, space, and geological research.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Because of international cooperation in oceanography and meteorology, there is a high level of international activity and capability directly relating to important military applications. These efforts all contribute to our understanding of and ability to model complex tactical conditions and scene dynamics.

Ongoing research and development . the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Undersea acoustic research, especially that correlated with bathymetry data
- Accurate predictions of localized weather conditions

- Effective integration of remote sensing data
- Improved modeling and simulation of scene dynamics.

The table on the following page provides a summary comparison of the United States and other nations in the key areas of this technology.

The Soviet Union is most capable in some areas of the weapon–target environment (e.g., the theoretical and mathematical aspects of underwater acoustics. The United States and its NATO partners lead in the tactical employment of environmental products due to a technological lead in high–technology computers and related software and hardware.

DoD capabilities in weather forecasting exceed those of the Soviet Union for most of the globe. For example, U.S. tropical cyclone forecasting capabilities far exceed those of the Soviet Union. However, in the Arctic, a more significant region tactically, Soviet knowledge of weather exceeds that of the United States because of greater experience, better facilities (such as ice–breaking research ships), and a broader resea h base.

It is generally accepted that the European Cent for Medium–Range Weather Forecasting is the finest facility in the world for producing highly reliable and accurate 3– to 5–day weather forecasts. However, sub–grid scale phenomena and subtle changes in atmospheric fields critical to 3– to 48–hour forecasting, especially over the oceans where data is scarce, continue to prove troublesome even for this facility.

Agreements with NATO and other Western nations are common in environmental research. The global nature of the atmosphere and the oceans makes such cooperation comfortable and obvious. An example of an existing agreement involves work with the Germans on the interpretation of synthetic aperture radar signals from the sea surface. NATO supports a major laboratory at LaSpezia, Italy, which is directed toward understanding the ocean sciences and their effect on ASW. Recent studies have stressed shallow water ASW as a high priority for our NATO allies. The Army has a data exchange agreement with Canada on atmospheric effects, and is participating with other NATO countries in a major field evaluation of EO/IR sensors under a variety of atmospheric conditions.

With increasing reliance on satellite–based remote sensing, technologies for improved collection and integration will advance and proliferate. Increasing interest has been noted on the part of such countries as Japan, China, India, and Brazil to deploy and operate their own remote sensing satellites. These are generally lower resolution (100+ meter) multi–spectral systems that fall below the 10–meter resolution of the French SPOT system. They represent a significant advance in capability for these nations. Japan, in particular, has plans to develop and deploy a number of satellites for both ocean and land observation. One, scheduled for launch in 1992, is to carry a high resolution (18–meter) all–weather radar and stereoscopic multi–spectral optical sensors (visible and infrared).

2. Exchange Agreements

There is a moderate level of exchange activity in the area of oceanography, weather, and atmospherics. Several NATO Research Study Groups (RSGs) of the Defence Research Group (DRG) (especially the RSG on Optics and Infrared Technologies and the RSG on Maritime Remote Sensing) provide a potential mechanism for exchanges of fundamental scientific information in underlying areas of interest.

The Technology Cooperation Program (TTCP) provides a vehicle for a range of applicable exchange relating to both undersea systems and atmospheric propagation.

Summary Comparison — Weapon System Environment

Selected Elements	USSR	NATO Allies	Japan	Others
Undersea acoustic research, especially that correlated with bathymetry data	□□□ ○	□□□ ○	□□	
Accurate predictions of localized weather conditions	□□	□□□□ ○	□□	
Effective integration of remote sensing data	□□	□□□ –	□□	□□ Various nations
Improved modeling and simulation of scene dynamics	□	□□	□	
Overall[a]	□□□ –	□□□ ○	□□	□□ Various nations

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□	broad technical achievement; allies capable of major contributions
□□□	moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
□□	generally lagging; allies may be capable of contributing in selected areas
□	lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

+	Foreign capability increasing at a faster rate than the United States
○	Foreign capability increasing at a similar rate to the United States
–	Foreign capability increasing at a slower rate than the United States

The Services have a number of exchanges, in NATO and with a few other friendly nations, in areas of specific interest. Among the areas represented by these exchanges are oceanography, undersea acoustics, and atmospheric effects on IR sensors and propagation. Programs with France and the UK are focusing on the effects of atmospheric electricity and electro-magnetic effects on aircraft.

The exchanges in characterization of the atmosphere in selected regions of the spectrum support key tactical weapons, strategic defense, and wide-area surveillance and intelligence. Different aspects of basic atmospheric physics and sensor performance are covered under Air Force, TTCP, and NATO DRG exchanges.

A number of agreements in the area of applied oceanographic and undersea acoustic research exist; however, because of the relationship to ASW, these tend to be classified programs and restricted to NATO allies except in cases where there is a clear quid pro quo.

12. DATA FUSION

12. DATA FUSION

A. DESCRIPTION OF TECHNOLOGY

Dramatic advances in data processing technology have enabled significant advances in command, control, communications, and intelligence (C3I) and battle management during the past 20 years. Data processing technology has advanced to the point where many functions previously performed by military operators and intelligence analysts can be performed effectively by data processing systems. The increasing complexity and speed of warfare, when combined with rapid advances in computer and communications technologies, are forcing a more effective integration of multiple sensors and diverse sources of information. Data fusion is the process of associating, correlating, and combining data and information from multiple sensors and sources to achieve refined position and identity estimation and complete timely assessment of situations and threats and their significance. Underlying technology development areas include collecting and modeling target and environment signatures, algorithms, probability and statistics, spatial/temporal reasoning, decision-aiding cognitive sciences, parallel processing, simulation, testing, and verification, heterogeneous systems integration and multi-level security processing capabilities.

Technology Sets in Data Fusion

- Theoretical foundations
- Algorithm and model development
- Data and knowledge base for fusion processing
- Development of reasoning systems
- Applications

Data fusion technology includes data processing techniques for a wide range of military applications from sensor cueing to cockpit display integration. It involves acquiring, transferring, integrating, filtering, correlating, and synthesizing useful data from diverse sources for the purposes of situation/environment assessment, planning, detecting, verifying, diagnosing problems, command and control of operating forces, aiding tactical and strategic decisions, and improving system/sensor performance and utility. In addition to military applications, high-speed, low-cost, reliable techniques for data fusion are increasingly applied to automated manufacturing. Also, developments in improved testing and verification methods and heterogeneous systems/sensors integration should find important commercial applications.

Data fusion is an integral part of all military systems from simple weapons to the most complicated large-scale information processing systems. It is essential that the military establishment develop a better understanding of the process of data fusion and a better set of tools to incorporate data fusion in emerging systems.

Data fusion is deceptively simple in concept but enormously complex in practice. Fusion deals with the management of uncertainties associated with data and knowledge. Appropriate mechanisms to deal with uncertainties in support of decision processes must consider not only data and source specifics but the environment under which observations are made and the context in which decisions may be applied. Data fusion technology is required to achieve the information gains expected from employment of multiple sensors/sources. Proper application of such technology mitigate sensor and communication overloads in modern systems and can contribute to improved operational utility.

Specific benefits attributed to data fusion include:

- Identifying the important targets
- Managing data glut
- Promoting communications viability
- Creating and maintaining a consistent operational picture.

In addition, data fusion complements other technologies in providing:

- Robust operational performance
- Extended spatial estimating and coverage
- Extended temporal estimates and coverage
- Increased confidence/reduced ambiguity
- Improved detection/identification
- Improved system reliability.

Data fusion technology will impact the following areas:

- *C^3 systems improvements*: Data fusion provides the basis for information processing and sensor management which is important to surveillance activities, advanced "smart" and "brilliant" weapon systems, and the design of advanced computer–supported military/political command centers. Data fusion fulfills essential processing and coordinating roles within multi–source, multi–platform, and multi–user systems. Application of data fusion implies assured connectivity between system elements and fusion center, timely communications, distributed data bases, and extensive interoperability.
- *Spatial/temporal data base systems*: Improved data base systems are required to manage large data/knowledge bases that avoid the combinatorial search space size often necessary to extract relevant data using conventional approaches. Applicable technologies include data base design and structure, new and efficient search and retrieval mechanisms, and distributed multi–media data base management. Rapid display in user–friendly flexible formats are important issues for decision support. Intelligent data base shells offer higher level, more abstract data base interaction and speed up application development.
- *System integration and product use*: Estimating sensor outputs, communications network capacity, transit times, user query traffic, and the effects of the system's products on its own operation implies strong design and management authority over both services and functional communities. This degree of control in complex

technology development programs does not yet exist. A user's access to data fusion products presents alternatives that could significantly affect the performance of the data fusion system itself. Because some user's may wish to ignore, exploit, deceive, jam, or destroy enemy systems that the data fusion system is using as critical inputs, it is critical to develop mechanisms for adjudicating conflicts in use of data fusion products before the system becomes operational.

- *Reasoning systems for situation and threat assessment:* Automated interpretation of data and information products are needed that consider the operational situation and decision objectives. Proper interpretation of data inputs and data driven products (e.g., target tracks and identities) to support situation and threat assessment for military commanders, requires reasoning about data in a larger context which includes doctrine (red and blue), environment, topology, and other considerations. Reasoning systems are essential to make judgements about data adequacy, deception and countermeasures, and data collection optimization. Developmental issues include (1) how much automated decision support is useful, (2) technologies which exploit models of human cognitive processes, (3) reasoning about trends to support resource allocation, and (4) guidance for physical design requirements of operator–machine interfaces.

B. PAYOFF

1. Impact on Future Weapon Systems

Data fusion technology offers significant opportunities for advanced battle management and C3I systems. Future combat operations will be faster and more lethal than in the past. Commanders will have considerably less time to make decisions and much more data on which to base those decisions Commanders' decisions will have more significant and far–reaching consequences than in the past. Without some form of automated data fusion, military leaders may be overwhelmed by data that could contribute to errors in judgment or delay of decisions and lead to catastrophic results.

The demand for data fusion capabilities has reached a critical level because of a number of operational technological and threat–related developments. The evolution of U.S. operational doctrine emphasizing deep attack and interdiction capabilities also creates a demand for information describing the location, movement, and intentions of targets that exceeds the performance level of conventional sensors currently in use. Present autonomous weapons, developed to execute deep–strike missions use programmed instructions to guide them to the target. Future combat vehicles, vessels, and aircraft will be designed to exhibit very low signatures to radio frequency and infrared (IR) sensors. To preserve this low observability, they will rely on passive sensors and information received from remote sources. Fusion of these inputs is an essential step in the development of the situational awareness required for survival and effective operation.

Data fusion techniques are essential to counter adversary use of stealth technology (e.g., acoustic quieting, low radar cross sections, low IR signature) and to aid in wide–area target surveillance during combat. Data fusion is particularly important for global or large–area surveillance and targeting. It will assist theater and lower echelon commanders in wide–area surveillance from space as well as undersea, predicting environmental conditions, and managing distributed assets (e.g., ECM and ECCM). Data fusion will also assist operators such as Advanced Tactical Fighter pilots in their future "super cockpit" or helicopter pilots with their nap–of–the–earth navigation. These passive sensors will need to be multispectral with radar sensors via cueing to provide real–time surveillance capability.

Future military operations will include low intensity conflicts, special operations, and counter narcotics activities. In support of law enforcement to counter narcotics activities, data fusion is required to integrate sensor and intelligence data in order to perform detection, monitoring, and reporting of illegal activities. In combat, fusion provides the coordination necessary to support command and control of distributed forces (often multi–service or multi–national) by creating and maintaining a consistent tactical picture, essential for the direction of all participants. Data fusion techniques are important in aggregating necessary data concerning hostile forces and operating arenas, and in distributing the data in consistent, usable formats to combat commanders. These requirements must be met efficiently, often with little warning or preparation time. Coupled with sophisticated data bases, data fusion will provide the automation necessary to support assessment of new situations and threats, and to provide tactical planning alternatives and advisory data. Such tools are essential where knwoledge of terrain and enemy force capabilities is limited.

2. Potential Benefits to industrial base

High–speed, low–cost, reliable techniques for data fusion are of growing importance to automated manufacturing, in the defense and commercial sectors. Real–time process control, sensor–directed cells and workstations, and robot and effector manipulation are three examples of manufacturing initiatives aimed at making products faster and with higher quality, which will require advances in data fusion technology. Other areas that could prove to be of substantial benefit to the commercial sector include heterogeneous systems and network integration aimed at developing distributed operating systems and multi–level secure networks, allowing the interchange of processing between disparate processors, (e.g., when equipment made by unrelated companies must interface). Multi–level security technology is highly applicable to commercial industry which needs to securely control access to sensitive corporate information and trade secrets. Data fusion offers significant new possibilities for security systems and unauthorized entry control. The fusion of information from various sources (passive ESM, IR, acoustic, motion detectors, fire and water detectors) can portray a home or business protected from intrusion or fire. Another area that shows great commercial promise is development of spatial/temporal data base management structures for industrial and financial applications. This technology could reduce search times, computational loads, and software coding requirements.

DoD data fusion applications requiring development of sophisticated distributed database systems is appropriate for civil sector: urban planning; resource management; pollution monitoring and analysis; and climate, crop, and geological analysis, supporting efficient information sharing among diverse agencies and organizations. The development of intelligent data base shells will simplify and reduce the development time of application software by supporting higher level interaction with the data base system.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Theoretical Foundations

(1) Objective

Develop a unifying theory of data fusion, including canonical forms for data fusion processes and consistent mathematical bases for future technological development. This area also addresses the requirement to properly categorize data fusion techniques in terms of their problem domains and solution potentials, and to understand the underlying processes in generic terms and with respect to specified metrics.

(2) Development Milestones

- 1992 – Process functional decomposition
- 1993 – Establish canonical forms for fusion process
- 1993 – Deterministic, probabilistic, fuzzy inferencing
- 1994 – Theory of plans, plan recognition
- 1996 – Theory of plan development
- 1997 – Conditional event algebra

b. Algorithm and Model Development

(1) Objectives

Develop simulation, correlation and assessment techniques, and metrics.

A robust environment for measuring multi-sensor, multi-platform, multi-user interactions must be developed. In order to evolve a consistent set of engineering guidelines for applying and evaluating data fusion theory and techniques, The complex spatial, temporal, and contextual processes which are the heart of the data fusion algorithms require laboratory environments for development and field environments for evaluation and testing. Simulations and testbeds for relating the dependence of data fusion metrics to sensor/source capabilities, doctrinal and environmental knowledge, and decision support requirements are needed.

Some laboratory and limited operational applications of multi-sensor and multi-source trackers relying primarily on kinematic data are available for military commanders to estimate target activity. Additional development in this area is essential to help decisionmakers absorb more diverse data from an increasing number of sources. The potential exists for automatic correlation and assessment of a variety of data, including target classification attributes, intermediate trace products for rapid assessment, contextual information for background understanding, and system control derived from fused product consistency with mission objectives in a knowledge-based system.

Current algorithm assessment techniques are application specific and are not supportive of rapid, consistent development of technology required for a broad spectrum of DoD systems. This area emphasizes comparative analyses of competing processes, identification of common (application independent) metrics, and their relationship to significant engineering and operational measures (MOPs and MOEs).

(2) Development Milestones

- 1991 – Multi-sensor target classification
- 1992 – Experimental use of tactical Fusion Testbed
- 1992 – Test of correlation functions
- 1993 – Knowledge-based shell for correlation
- 1994 – Testbed with parallel computer architecture
- 1994 – Test of nondeterministic processes
- 1995 – Sensor management and control

c. Data and Knowledge Bases for Fusion Processing

(1) Objectives

Underlying the data fusion problem is the need to relate observations from sensors to representations of the battle space. All DoD systems integrate a broad range of sensor/source data with doctrinal and contextual data all of which must be user-friendly to all levels of the command structure. This area addresses development of more efficient data base design and structure, new and efficient search and retrieval mechanisms, and distributed multi-media data base management.

Spatial/temporal data bases and domain knowledge bases support the processes of correlation and assessment. To support human analysts, a data base must support rapid search and display in easily accessed formats and must have content which is accurate and reasonable. Emphasis is on human computer interaction (HCI) and techniques to ensure data base integrity and consistency between multiple users and processes. This includes the need for synchronous, multi-sensor test data, referenced to ground truth, which is representative of differing operational environments. As data bases grow larger, advanced optical media and holographic techniques will be required to achieve higher density storage and quicker retrieval.

(2) Development Milestones

- 1991 – Multisensor surveillance data (air)
- 1992 – Hybrid spatial data base management system (front end)
- 1993 – Multisensor surveillance data (surface)
- 1994 – Hybrid spatial, object oriented data base management system.

d. Development of Reasoning Systems

(1) Objectives

Proper interpretation of data inputs requires reasoning about data in the larger context of doctrine (red and blue), environment, topology, and related issues. There is a need to exploit models of human reasoning and for automated interpretation of data and information products considering operational contexts and mission objectives. The evolution of automated correlation and reasoning systems dealing with data and contextual information opens new possibilities for partitioning functions between human and machine. This area addresses the degree and type of automated decision support to be provided by data fusion systems for both operational and developmental purposes. Reasoning systems must reason about data trends, hostile intentions, and mission objectives in order to optimize data collection and resource allocation while dealing with ambiguous data.

(2) Development Milestones

- 1993 — Computational geometry for spatial reasoning
  Real time resource allocation
- 1993 — Neural nets for situation assessment
- 1995 — Multi-hypothesis reasoning
  Automated template authoring
- 1996 — Sensor parameter control
- 1997 — Spatial/temporal reasoning system.

e. Applications

(1) Objectives

Demonstrate practical systems employing automated data fusion.

(2) Development Milestones

- 1992 — Transition submarine contact management algorithms to systems
- 1993 — Demonstrate ASW workstation using acoustic and nonacoustic sensors
- 1994 — Demonstrate EW effectiveness monitoring and control
  Demonstrate multisensor EW
  Demonstrate ASW acoustic data fusion processes
- 1995 — At-sea demonstration of fusion of on- and off-land sensor data
  Demonstrate multi-platform air-to-air sensor fusion *
  Evaluate ship classification techniques using multisensor inputs

F. AUTOMATIC TARGET RECOGNITION

1. Objectives

Use automatic target recognition (ATR) techniques to reduce the information overload flowing from an integrated command and control function that exploits data from a variety of sensors and sources.

Model–based ATR systems exist in the laboratory, but much more work is needed to build reliable operational systems. There are four major components to ATR research that need to be advanced to realize the objective of reliable, robust operational ATR systems: theoretical framework for ATR, paralleling that for data fusion is vital; continued improvement of algorithms to exploit improvements in the performance and variety of sensor systems and in the capabilities of modern digital processing equipment; more sophisticated algorithm development and evaluation testbeds to address the diversity of target signatures and background clutter against which they must be detected and recognized; and improved parallel software, languages, and operating systems, to permit the real–time implementation of sophisticated, model–based ATR algorithms.

2. Development Milestones

- 1991 – Develop model–based ATR algorithms for multi–sensor (e.g., laser radar range and intensity imagery) data.
- 1992 – Develop model–based ATR algorithms for polarimetric millimeter wave synthetic aperture radar imagery.
- 1993 – Combine sensor data with map data to improve recognition performance and develop initial situation assessment capability.
- 1994 – Fuse data form multiple platforms for target recognition and assessment of changes in situations.
- 1995 – Demonstrate real–time ATR function in airborne testbed.

2. Technology Objectives

Technology Objectives — Data Fusion

Technical Area	By 1997	By 2002	By 2007
Theoretical Foundations	• Functional decomposition • Unified model: matching of solutions to problems	• Conditional event algebra	• Advanced algorithm research — neural — biological
Algorithm and Model Development	• Real-time fusion of track, ID, and weapon control • Real-time fusion of distributed surveillance sensors • Multi-national data fusion demonstration	• Automated sensor management • Real-time distributed fusion for track and ID surveillance • Resource allocation to counter low observables and jamming • Multi-spectral/multi-mode sensor • Integrated signal detection, processing, and control	• Automated sensor parameter control • Situation assessment supported by track and ID fusion using organic and non-organic sensors
Data and Knowledge Bases	• Spatial/temporal DBMS • Multi-sensor surveillance data -- selected applications	• Distributed asset - oriented DBMs • Domain knowledge for platform-based expert systems	• Advanced storage media — 3D holographic memory — other optical — multi-media
Reasoning Systems	• Real-time advisory system using multiple sensors • Automated message filtering • Automated template authoring system	• Plan recognition capability using multiple sources • Spatial/temporal reasoning systems	• Plan prediction capability • Plan supervision and replanning support • Automated situation and threat assessment

3. Resources

Total S&T funding[11] for this critical technology is shown in the table below.

Funding — Data Fusion ($M)

FY-87-91	FY92	FY93	FY94	FY95	FY96	FY97
288	106	109	108	98	98	93

4. Utilizing the Technology

Data fusion programs are becoming more evident in operational and system applications. Programs that fall into the category of C3I require the most fusion and the higher the echelon the more data fusion is required. The Joint Tactical Fusion Program developed and fielded LOCE (Limited Operational Capability Europe) and LENSCE (Limited Enemy Situation Correlation Element) to provide automated intelligence support to tactical Army and Air Force commanders. These systems were derived from BETA (Battlefield Exploitation and Target Acquisition) and represent a stage of an evolutionary process to improve the usefulness of fielded systems. In the current evolution the Army is developing ASAS (All Source Analysis System) and the Air Force is developing ENSCE (Enemy Situation Correlation Element). These systems will support the operations and fire support elements as well as the intelligence officer and will provide an integrated picture of the battlefield.

Within the Navy, the Naval Command and Control System (NCCS) is evolving as the principal operational support system. NCCS encompasses the Tactical Flag Command Center (TFCC) afloat, and the OSIS Baseline Upgrade (OBU) ashore. These systems have a strong intelligence processing side and support high level command. TFCC also provides tactical displays and integrated information management for all command levels. At an intermediate level the Navy has several systems for correlating unique or organic battle group data. These include Electronic Warfare Coordination Module (EWCM), Prototype Ocean Surveillance Tracker (POST), Afloat Correlation System (ACS), and others. These will be incorporated into TFCC.

The focus of avionics applications the focus is on crew support and problems dealing with reasonably bounded systems employing controlled organic sensors. The avionics community has been stimulated by such programs as the Integrated Electronic Warfare System (INEWS) and the Integrated Communication, Navigation, and Identification Avionics (ICNIA) system. A full feedback data fusion system in the integrated control for air-to-air superiority (ICAAS) program is now under development. At an even lower level, missile seekers must perform fusion. The advanced medium range air-to-air missile (AMRAAM) program in the Air Force uses data fusion as part of its track and acquisition function.

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[11] Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

The wide-area mine system has been augmented by acoustic and seismic sensors that can detect vehicles at greater ranges, and provide target discrimination. After the target is distinguished, it is located and attacked by appropriate means. The mine is equipped with sufficient electronics to perform the data fusion without human assistance.

The inter-vehicular information system/radio interface unit segment of the M1A2 tank system provides real-time processing and distribution of combat information to enable the integration and synchronization of critical battlefield information at battalion level and below.

D. LEVERAGING DOMESTIC INDUSTRIAL BASE CAPABILITIES

1. Current Domestic Industrial Capabilities

Data fusion requires communication systems and networks (with high data throughput) that are survivable in the face of enemy jamming, interception, and spoofing. Multi-computer systems for distributed data processing and distributed data base systems with the software and software engineering technology to run them are required. Graphics software, advanced displays, and visualization technology linked with human-computer interface and human factors engineering also are needed. From a manufacturing perspective the ability to fuse data across organizations is of fundamental importance. Development and manufacture of high-resolution, flat-panel displays is also important to data fusion. DBMS evolution and associated improvments in storage hardware will provide the basis for important gains in industrial management such as inventory control and resource allocation. Developments in reasoning and cognitive processes will support robotics in manufacturing.

The essence of this critical technology is that disparate sensor information is appropriately preprocessed, melded, while only pertinent information is extracted and presented. The components of technology required to build systems of this type are contained in infrastructure technologies (e.g., semiconductor materials and microelectronics circuits, active and passive sensors, and parallel architectures). However, the fact that manufacturing processes can exploit subsets of this technology is of fundamental importance to the industrial base. Real-time process control, sensor-directed cells and workstations, broad application of robotics, built-in diagnostics, and automated control are examples of manufacturing concerns requiring data fusion.

Other current manufacturing process capabilities include:

- Parallel processors (DAP, Connection Machine, Torgue, Touchstone)
- Expendable fiber-optic gyros (for use in smart, expendable sensors)
- Surface acoustic wave devices (cheap, small, frequency analysis devices for sensors)
- Microelectronic packing.

2. Projected Domestic Industrial Capabilities

Manufacturing advances will depend largely on developments in computer and communication technologies, automated decision making (well beyond current expert system technology), and other process-level activities. Artificial intelligence related efforts, including those directed at self-improving capability to enhance system performance and the extraction of understanding from multiple data sources, are particularly critical. Advances will come primarily from computer software and systems integration industries.

Other contemporary DoD manufacturing technology investments supporting and utilizing this critical technology include: developing information engineering tools to support planning, analysis, and design of factory-wide information systems; participating in industry-wide, machine-to-machine interface and communications standards; and developing factory modeling and simulation techniques to assist in transferring products from design to production.

On a systems level, data fusion will be spurred by investments from Strategic Defense Initiative Office (SDIO) and DARPA initiatives, such as Pilots' Associate. However, none of these systems-level investments directly motivate domestic manufacturing, nor will they directly demonstrate how data fusion can be used to make products faster and with higher quality.

Other projected manufacturing process capabilities which will improve data fusion capability include:

- Diamond fiber composites (conformal fuselage windows for sensors)
- Phased array IR and visible wavelength semiconductor lasers (for electronically steered Ladars)
- Integrated optical data processing (image processing for target detection and classification)
- Nanotechnology (precision assembly of molecule-sized sensors, processors)
- Holographic optical interconnect (massive interconnections for parallel processing).

E. RELATED R&D IN THE UNITED STATES

There are many similarities between the distributed processing technology efforts in U.S. industry and DoD data fusion efforts. There should be beneficial interaction between DoD and industry as applications proliferate. Most of the software and computer hardware technology is being developed by industry. Establishing standards and protocols that encourage growth in distributed processing technology, while allowing users flexibility in system configuration, is critically important in the development of large-scale data fusion systems.

NSF supports research in information theory related to combining data from multiple sources, including the detection and processing of data from distributed sensors.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

Ongoing international research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Enhanced man/machine interface

- Rapid assimilation and processing of large data sets
- Data fusion algorithms for real-time analysis of large data sets
- Real-time operating systems for secure distributed processing
- Intelligent data extraction from text and pattern recognition (including application of neural nets).

In addition, detailed characterization and modeling of targets and sensor responses, propagation, and noise phenomena (see signal processing and weapon systems environment) will be key elements.

The table on the following page provides a summary comparison of U.S. and other nations for selected key aspects of technology that support the data fusion process. Principal cooperative opportunities will exist with NATO countries, especially in technologies coming out of the European Strategic Program for Research in Information Technology (ESPRIT) program.

U.S. technology for the production of software-based systems is far ahead of that of potential adversaries. Several factors are dramatically affecting international developments in data fusion, and the potential for both our allies and adversaries to make progress in this area: the growing international exchange or transfer of the technology for powerful data acquisition systems and the low-cost computing systems to support them; the growing international realization of the importance of data fusion technology to future military C3I systems, a technology which will have ever widening applications in systems that have computers supporting real-time signal data analysis and the increased emphasis by the developed military powers on distributed, survivable, real-time command and control.

France appears well advanced in concepts for the application of AI and low-cost workstations to real-time battle management. The UK is a leader in automatic aircraft flight control, a key application of data fusion, has an ongoing program in parallel processing, and the Vehicle Electronics R&D Initiative (VERDI). Germany has an active program in the area of command and control of armored forces, including introduction of data fusion, with machine intelligence and robotics into future improvements to the Leopard II.

Japan has a substantial lead in display device and component research and development activities, and the United States is dependent on these sources for cockpit displays in such aircraft as the F/A-18, and AV-8B. Support through Japan's Ministry of International Trade and Industry (MITI) and funding provided by a consortium of private Japanese companies interested in the development of high-definition television (HDTV) are primary drivers for advancements in data fusion technology. These will contribute directly to enhancing man/machine interfaces for rapid assimilation of data.

With regard to real-time multiprocessing, the Japanese BTRON project has, as one of its reported objectives, the development of an open real-time operating system that will be downward compatible with existing standards. This work has been ongoing for some time and Japanese companies have produced prototype microprocessors incorporating certain of these features. However, progress to date appears to be short of initial expectations.

While the United States continues to hold a lead in the area of intelligent data extraction from text, Japan, as well as a number of NATO allies, are actively pursuing pattern recognition for commercial applications -- most notably text (and possibly in the future, speech) translators.

Summary Comparison — Data Fusion

Selected Elements	USSR	NATO Allies	Japan	Others
Enhanced man/machine interface, rapid assimilation and processing of large data sets	□	□□□ O	□□□ +	
Data fushion algorithms for real-time analysis of large data sets	□□	□□	□□	□□ Israel
Real-time OS for secure distributed processing	□	□□□ O	□□	
Intelligent data extraction from text; pattern recognition (including application of neural nets)	□□	□□	□□□ O	
Overall[a]	□	□□	□□	□□ Israel

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

- □□□□ broad technical achievement; allies capable of major contributions
- □□□ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
- □□ generally lagging; allies may be capable of contributing in selected areas
- □ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

- \+ Foreign capability increasing at a <u>faster</u> rate than the United States
- O Foreign capability increasing at a <u>similar</u> rate to the United States
- — Foreign capability increasing at a <u>slower</u> rate than the United States

Even as the impetus for introducing this technology into weapon systems increases, requirements for commercial applications, such as, transportation safety, air traffic control, nuclear power plant safety, and other complex transaction systems are beginning to overlap into areas of military capability. These will stimulate continued growth in all areas of technology related to data fusion.

2. Exchange Agreements

While data fusion as an isolated field of technology is not explicitly represented in the listing of international agreements surveyed, it is a pervasive subset of many other areas. NATO Defence Research Groups (DRGs) studies in identification of submarines, defense applications of operations research, electronic warfare concepts and technology, and long-term research related to air defense all require, or will help to define requirements for, data fusion.

The Technology Cooperation Program (TTCP) provides a vehicle for exchanges in related areas of weapons, computers and software, applications of artificial intelligence, and other topics that form part of a viable supporting infrastructure for data fusion. In addition, TTCP activities include many topics (active aircraft control technology; data integration for undersea warfare; and radar, IR, and EW system cueing) that are related to data fusion.

DoD is involved in an extensive cooperative program with the UK in the area of data fusion for strategic defense. The UK is especially interested in the development of parallel processing and artificial intelligence technologies to enhance data fusion capabilities.

Data fusion is a key element of a number of the Service weapon system-related exchanges. Service exchange agreements exist for definition of multi-function information distribution systems, cooperative communications, advanced attack helicopter mission equipment package, and cooperative measures to enhance sensor/multi-input intelligence data fusion. Similarly, advanced flight control concepts, aircraft mission equipment, and main battle tank and naval tactical data systems/combat management will entail real-time fusion of inputs from large numbers of sensors and control feedback mechanisms distributed throughout the platforms, as well as the integration of such data with information from external resources.

13. COMPUTATIONAL FLUID DYNAMICS

13. COMPUTATIONAL FLUID DYNAMICS

A. DESCRIPTION OF TECHNOLOGY

Computational fluid dynamics (CFD) encompasses the calculation of fluid flow around bodies for all speed regimes and in any type of fluid–gas, liquid, or even solid (under special circumstances). The fundamental equations of fluid flow, the Navier–Stokes equations, were first derived in 1827. Under the assumption that the fluid is a continuous medium, the Navier–Stokes equations are considered to be exact and to apply to even the smallest observable eddies of turbulence. However, the equations are very complex three–dimensional, nonlinear partial differential equations in four independent variables (three space dimensions and time). Because of these complexities, the governing equations cannot be solved analytically except for the simplest cases and geometries. Therefore, computational techniques are used to solve the equations via numerical procedures on high speed computers. Solutions of the full Navier–Stokes equations for flows with turbulent boundary layers require tremendous amounts of computer resources. The result is that currently many CFD methods solve simplified versions of the equations. Foremost among these is the use of simple models of small scale turbulence (turbulence models). Elimination of the viscous stress terms produce the Euler equations. Liquid flows may be assumed to be incompressible which eliminates variable density terms. On the other hand, at conditions where the continuum assumption no longer applies, such as at high altitude and high velocities, the chemical constituents and molecular statistical interaction properties of the fluid must also be included in the calculations. This significantly increases the computational effort.

Technology is being developed and used to calculate fluid flow past or through bodies of interest to each of the Services and DoE to develop improved flight vehicles, ocean vehicles, air–breathing engines, and weapons including armor and anti–armor warhead design. For conventional systems, such calculations greatly reduce both development cost and time. For most conditions and concepts designed to operate at speeds above Mach 8, CFD is the only way to determine the forces, moments, and heating of the vehicle. Overarching all of CFD technology is the problem of validation of the codes, recognizing that even the most complex codes are still only approximations. This requires carefully conducted experimental procedures. Validation for conditions where experimental data cannot be obtained is a serious concern.

From a software perspective, other key CFD development problems exist in the areas of turbulence modeling, three–dimensional grid generation, and solution methodology. Massively parallel computing architecture and algorithms are major developmental areas certain to produce a huge (10,000 times) increase in CFD capabilities over current supercomputers. Secondary development problems involve algorithm development, complex geometry definition, and pre– and post–data processing. From a hardware perspective, mainframe computer methodology and architecture also warrant advances.

This critical technology will become a design tool, much like the wind tunnel, to increase the performance and effectiveness of aircraft, missiles, and hypersonic vehicles. CFD can be applied to a wide spectrum of concepts such as high–angle–of–attack aerodynamics, airframe–propulsion integration, rocket and turbine engine propulsion, weapons integration, and conventional and high–energy weapons. Coupled with other disciplines (e.g., structures, trajectory flight dynamics, optics, electromagnetics, and low observables), CFD can revolutionize the design process for flight vehicles, exploring space well beyond that offered by conventional design methods. In addition, there are major applications in the design of submarines and ocean vehicles and specialized high–performance parachute systems. CFD technology is also important for analyzing improved propellants for missiles and guns and superior gun–launched projectiles and missiles.

Technology Sets in Computational Fluid Dynamics

- Computations of unsteady aerodynamic phenomena
- Hypersonic flow solutions
- Turbulence Modeling
- Internal Flows
- Pre–processing (geometry and grid generation)
- Validation of CFD codes

B. PAYOFF

1. Impact on Future Weapon Systems

CFD will accelerate development, lower design risks, and reduce costs of all future flight vehicles that currently cannot be tested in restrictive flight regimes. CFD will be used to rapidly identify promising design concepts before wind tunnel tests are conducted, significantly reducing system development time. Current wind tunnels cannot test even modestly sized full–scale aircraft at speeds above 200 mph (Mach 0.3), or vastly reduced scale models at speeds above Mach 8. At high Mach numbers the available test conditions do not simulate high Reynolds–number turbulent flow conditions. CFD may be applied to explore the combined influences of both high Reynolds–numbers and high Mach numbers. CFD is used and will be used to design and evaluate higher speed vehicles such as hypersonic interceptors, reentry vehicles, hypersonic missiles, and low–cost expendable rockets. This technology can be applied to all classes of aircraft and missiles to improve performance and mission effectiveness. CFD can address a wide variety of problems for current and future aircraft and helicopters, including airframe/propulsion integration, airframe/weapon integration and separation, aerodynamic/aeroelastic structure interactions, aeroacoustic/structural interactions, and radar/infrared signatures.

Critical enabling technologies for the National Aerospace Plane (NASP) are CFD; lightweight, high–strength, high–temperature materials; and advanced technology propulsion. The ability to accurately predict pressures and heating in flight and propulsion system performance is vital to the development of the NASP vehicle. Based on the maturity of these technologies, a decision will be made early in FY 1993, on whether to proceed to develop the X–30 flight vehicle for flight tests in the latter part of the decade. From the lessons of the X–30 program, follow–on vehicles with true operational usefulness can be designed which will make access to space more routine and less costly. In addition, these NASP–derived vehicles will be able to perform military missions within the atmosphere at greater distances and at speeds much faster than today's airplanes.

Overall, CFD, with advances in computer hardware architecture, will provide design tools for surface ships and submarines to support quieter, more stable, and more maneuverable operations and make wide spectrum signature treatment possible. CFD will also be used for submarine and surface ship design to minimize expensive model testing and to provide the capability to quickly bring a concept to full–scale application.

Improved rotorcraft aerodynamics prediction made possible by CFD will enable the design of smaller, quieter, more survivable designs with low vibration levels, thereby reducing crew fatigue and improving weapons accuracy and component life. More agile and maneuverable rotorcraft will enhance the ability to fight and survive in air and ground attack in the nap-of-the-earth environment.

CFD has recently been applied to the analysis and design of high-performance parachutes. Parachutes are thought of principally for aircrew survival and airborne assault; however, they also are important components on a variety of advanced weapons, as well as in the recovery, evaluation, and reuse of expensive weapon systems, research vehicles, and instrumentation during flight tests. Within the past few years, parachutes were deployed at over twice the speed of sound and successfully delivered simulated weapon systems from aircraft flying only 100 feet above the target.

Flight vehicles operating at very low speeds present unique flow problems, which are readily addressed by the application of CFD. Such applications have led to the development of low Reynolds-number folding aerostructures that can provide new surveillance and targeting capabilities for both surface and undersea vessels, enabling them to perform missions not now feasible.

For ground forces, longer range artillery will provide a new capability in deep attack. Higher muzzle velocities will significantly affect anti-armor measures. Greater accuracy for gun-launched projectiles and missiles through better design is a major force multiplier.

2. Potential ˙ enefits to Defense Industrial Base

CFD has proved to be a powerful tool for the US aerospace industry for design modification and problem solving, and its use for the design of the next-generation of commercial aircraft is expected to help continue the current dominance of U.S. companies in the international marketplace. Its value is now being felt by the automotive engine design community.

Savings in the resources and time needed for advanced civil vertical take-off and landing (VTOL) and short take-off and landing (STOL) configurations development and test can be achieved by innovative advances in three-dimensional large-eddy turbulent simulations. This includes aeroelastic rotating blade and turbine flow field influences plus ground effects. Compressible CFD techniques with finite-rate chemical kinetics and multicomponent diffusion need to be developed for applications including hypersonic aircraft propulsion and integrated full-scale aircraft designs. The full three-dimensional fluid/solid surface turbulence interaction process calls for sophisticated advances in CFD to provide accurate aeroelastic information for advanced materials and configuration designs for highspeed flight, as well as to address the illusive aerodynamic problems associated with boundary layer flow separation and laminar to turbulent transition on lifting airfoil surfaces.

Another effect of CFD will be on the fluid dynamic and mass transfer analysis of manufacturing processes, such as the computer-aided production of silicon wafers using chemical vapor deposition in chip fabrication and in casting and coating machine parts. Studies have recently shown that small changes in the fluid dynamics can cause a significant improvement in quality and performance in the production of silicon wafers. CFD technology is mature enough to predict the deposition process in both continuum and non-continuum (very low density) conditions so that design improvements in chip production equipment can be made. Another area in which CFD can have a significant effect is the dynamic simulation of high-temperature, gas deposited coatings on materials, and welding, soldering, and casting of high-temperature metals. These manufacturing processes have important application to the production of circuit boards, machine tools, electrical components, gas turbine parts, and other industrial components suitable for high-temperature or corrosive environments.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Flight Vehicle Computations

(1) Objectives

Computational fluid dynamics techniques will be applied to improve the design of conventional fixed-wing aircraft, rotorcraft, and hypersonic aircraft. These capabilities will be used to address aerodynamic problems associated with high angle of attack, weapon and store separation, acoustics and airframe propulsion integration. Rotorcraft improvement will focus on wake modeling, retreating blade stall, acoustic and rotor-body interactions. For hypersonic vehicles, CFD calculations will address cooling, ablation interactions, and complex aerothermodynamic interactions.

(2) Development Milestones

- Aircraft design
  - — 1991 Static aeroelastic wing analyses
  - — 1992 Powered lift VSTOL analysis
  - — 1993 Dynamic aeroelastic wing analysis
  - — Wing pylon multiple store design
  - — 1994 Airframe propulsion integration
  - — 3-D wing analysis
  - — 1996 Unsteady aeroelastic wing analysis
  - — 1997 Aeroelastic aircraft dynamic motions
- Rotorcraft Design
  - — 1991 Hover free-wake analysis
  - — 1993 Improved turbulence models
  - — 1994 Rotor/body interactions
  - — 1997 Isolated rotor dynamic stall analysis
- Hypersonic vehicle design
  - — 1991 Blunt body analysis in real gas
  - — 1992 Validated, real gas capability High-speed aeropropulsion integration
  - — 1994 Multiphase flow, weapon separation and flight test simulation

— 1995 Initial, inverse CFD capability

— 1996 Aerodynamic/thermodynamic control

b. Propulsion System Computations

(1) Objectives

The 10-year goal for the application of Computational Fluid Dynamics to turbine engines is the simulation of the airflow through the entire engine including the compressor, combustor, turbine, coolant passages, and exhaust nozzle. Efforts will focus on developing a predictive capability for unsteady transonic viscous flows through the engine compressor and for flows through turbine coolant passages, drawing heavily on methods developed by other organizations including NASA Research Centers.

CFD efforts for rocket engines are grouped into two areas: rocket engine simulation and analysis and rocket engine plume analysis. During the next five years, efforts will be directed at improving combustor performance and stability for liquid fuel rockets and multiphase, grain deformation, and grain aeroelasticity effects for solid fuel rockets. Rocket plume methodology will address developing a UV signature prediction capability followed by the development of an IR/UV countermeasures model.

(2) Development Milestones

- Turbine engine design

  — 1992 3D steady, viscous rotor and stator analysis
  Enhanced boundary layer transport model

  — 1994 2D transonic viscous rotor and stator analysis
  Fuel and lubricants thermal kinetics

  — 1995 2D analysis of internal passage of turbine coolant

  — 1996 3D transonic, viscous rotor and stator analysis.

- Rocket engine design

  — 1991 Improved axi-symmetric analyses
  Liquid combustor performance analysis
  Plume ultraviolet signature predictors

  — 1994 Analyze stability of liquid combustion
  IR/UV signature countermeasures model

  — 1995 Grain aeroelastic flow effects analysis
  Inverse plume analysis

  — 1996 Stability assessment at high chamber pressures and
  burn rates

c. Weapons Computations

(1) Objectives

CFD has application to both blast and incendiary weapons. The ability to define and predict explosion blast effects is essential for the design of structures to survive deliberate or accidental explosions, and for the development of improved explosive devices. CFD has become a major tool for the analysis and prediction, and in some cases tailoring of the blast effects from explosions. Some experiments are still needed to validate new hydrocodes or to establish algorithms for other computer models.

The capability now exists to handle any Newtonian fluid–fills representative of existing chemical agents. Future work will concentrate on the more complex, non–Newtonian fluids such as viscoelastic liquids which are being considered for advanced antimateriel and flame and incendiary weapons. In this regard, CFD will be important in analyzing the mixing, dissemination and dispersion of these unusual payloads.

(2) Development Milestones

- Blast effects
  - — 1992 Statistical model of geological property variation
  - — 1994 FID adaptive grid ground shock and air blast model
  - — 1996 FEM share function optimization for ground shock and air blast
  - — 1997 FID curvilinear coordinate model for ground shock and air blast
- Flame and incendiary weapon design
  - — 1991 Analysis of immiscible addition and transients of Newtonian fluids
  - — 1993 Analysis of mixing phenomena of Newtonian fluids
  - — 1996 Analysis of additives of non–Newtonian fluids
  - — 1997 Analysis of transients in non–Newtonian fluids

d. Ocean Vehicle Computations

(1) Objectives

CFD will also be used to improve submarine design and to improve marine propulsion systems. A major objective is to reduce noise, and, at the same time, increase efficiency.

(2) Development Milestones

- Submarine design
  - — 1991 Submarine configurations without propulsors
  - — 1992 Advanced sea water pumps
  - — 1993 Composite rotor technology
  - — 1996 Submarine/propulsor configurations
- Advanced propulsion
  - — 1992 Asymmetric duct design

— 1993 Water jet-in-flow design

— Improved pump flow turbulence prediction

e. **Special Purpose Computations**

(1) **Objectives**

CFD can provide a detailed description of the motion of a parachute and the air surrounding it, in contrast to presently available prediction methods for decelerators which use lumped parameter models, containing no information about spatial distributions. This work will be the basis for new ideas and concepts for meeting the demanding airdrop systems' requirements for operation at higher speeds and lower altitudes, and with larger payloads. In addition, the ability to predict parachute behavior will allow a reduction in the need for testing during the development of airdrop systems, thus reducing expenditures of both time and money.

CFD will also be used to improve sea-state forecasting for both deep water marine operations and over-the-shore supply operations in coastal waters.

(2) **Development Milestones**

- Aerodynamic decelerators

  — 1991 Analysis of steady and unsteady deformable membranes with fluid and structure interactions.

  — 1995 3-D analysis of unsteady, porous, deformable membranes with turbulence

  — 1997 Model opening of full-scale, low-altitude, high-speed parachute.

- Sea-state forecasting

  — 1992 Sea-state data base for logistics over the shore

  — 1994 Current and water base model

  — 1997 Wave forecast model

2. **Technology Objectives**

Technology ObjectivesComputational Fluid Dynamics

Technical Area	By 1996	By 2001	BY 2006
Computational techniques	• Moving grid solver • Hypersonic weapon separation codes • CFD vehicle structure codes • Use of massively parallel architectures	• Real gas/ionization effects • Inverse methods that design rather than evaluate configuration	• Interdisciplinary inverse design methods
Hypersonic vehicles	• NASP • Hypersonic air-breathing missiles	• Hypersonic interceptors • Highly maneuverable reentry vehicles	• Low IR signatures • Hypersonic missiles • NASP-derived vehicles
Ocean vehicles	• 3-D Navier-Stokes for submarine applications	• Navier-Stokes for hydro-acoustic design of propulsors	• Inverse design with Navier-Stokes
Low Reynolds-number vehicles (low speed flight)	• VSTOL	• Com[illegible]ete demonstration vehicles	• Submarine-launched targeting and surveillance vehicle • Ship-launched decoy and jamming vehicles • Ship-launched high-altitude long-range reconnaissance vehicle
High-performance rotorcraft	• Validated Navier-Stokes computations of advanced rotor systems	• [illegible]ulations of new [illegible] [illegible]oncepts	• Highly maneuverable high-speed rotorcraft
High-performance parachutes	• Complete vortex panel models fo[illegible] predicting parachute flow fields • Develop and validate semi-empirical parachute infaltion codes • Extend decelerator technology into the hypersonic regime	• Plac[illegible] [illegible]peration an unste[illegible] aerodynamic ground test facility for simulati[illegible] parachute aerody[illegible]ics • Crew escape and paratrooper parachute systems configurations with greater reli[illegible]bility, and lower cost	• Complete development and validation of a full three-dimensional Navier-Stokes computer simulation of parachute inflation
High performance, large caliber guns	• Develop and validate end-to-end interior ballistics models for hybrid plasma/liquid propellant guns	• Simulate new [illegible] concepts that [illegible]mit the firing of smart projectiles	• Develop new electro-thermal-chemical weapons for shipboard and land-based use
Improved armor and anti-armor weapons	• Develop and incorporate materials strength models in two and three dimensions	• Accurate wa[illegible]ead of penetration models	

3. Resources

Estimated funding[12] for developing this technology is as follows.

Funding — Computational Fluid Dynamics ($M)

FY87-91	FY92	FY93	FY94	FY95	FY96	FY97
428	94	95	99	101	105	108

4. Utilizing the Technology

CFD is being used for: improving and extending our current aircraft capability; operating wind tunnel test facilities more efficiently; supporting flight test operations and flight safety; and technology development. Airframe and propulsion integration efforts are underway to develop high-performance inlet and exhaust nozzle concepts to incorporate STOL, high-agility, and supersonic cruise capabilities into low observable aircraft designs. Vortex flow control concepts are being explored to increase the agility and control of aircraft at high angles of attack. Design data are being developed that are critical for the integration of high-performance inlets and nozzles into Mach 4 to 6 aircraft. CFD has been identified as a critical technology for the NASP flight vehicle. A thorough understanding of aeroheating phenomena is required for high-speed flight vehicles to build efficient structures that can survive the extreme temperature environments. CFD has been used in the Advanced Tactical Fighter (ATF) and B-2 development programs for configuration development and airframe-propulsion integration. Wind tunnels are being enhanced to produce more accurate data for the validation of CFD codes. Key areas of research include low-turbulence, high Reynolds-number wind tunnels, hot-wire anemometry, and laser velocimetry. Future uses of CFD will include weapons separation, acoustics, signature control, flight path dynamics, and propulsion system simulation. These capabilities are directed at achieving the vision of an interdisciplinary inverse CFD capability where the desired characteristics are specified and the software defines a configuration which will exhibit those characteristics.

Advances in supercomputers and computational techniques will enable aerodynamic and aeroelastic calculations of complete rotorcraft to be realized before the turn of the century. This revolutionary capability, which has already been demonstrated for fixed-wing aircraft, will lead to major improvements in rotorcraft by providing better and more cost effective design tools; reducing risks for new configurations; enhancing performance, efficiency, and aeroelastic stability; and reducing vibrations and noise.

Current hydrodynamics activity includes the development of three-dimensional Navier-Stokes codes for submarine design. CFD work on ocean vehicles is expected to produce results that can be incorporated into an advanced technology demonstration in the 1990-95 timeframe. This technology will be able to support engineering development of submarines between 1995 and 2000. CFD technology should be incorporated in new ship designs beginning about 2010.

Conversion of our understanding about unsteady parachute aerodynamics into parachute design and performance prediction codes is the next step in parachute technology

[12]Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

development. Computer hardware and computational methods have progressed to the extent where numerical modeling of parachute inflation is feasible. Such feasibility is critical, as flight test costs have escalated to the extent that design-by-test is unaffordable.

DoD has unmanned autonomous vehicle programs that support the folding aerostructures development. This technology will be used by a joint acquisition program. By the mid-1990s, engineering development could be undertaken for three implementations: a submarine-launched target-acquisition and surveillance system; an off-board deception and jamming UAV; and a high altitude reconnaissance vehicle for long-range surveillance and warning for fleet air defense. DoD's gun-launched projectile and missile programs include studies of supersonic and hypersonic flow past finned projectiles, base flow phenomena, transonic/supersonic flow transition, and flutter divergence boundaries for supersonic missiles. In ballistics, fluid dynamics is key to the development of improved solid propellant guns. Propellants themselves are being investigated to determine optimal grain configurations based on control of propellant fracture, improved ignition systems, and associated traveling wave charge phenomena. A related part of this effort is also directed to such requirements as control of muzzle blast and minimizing flash. Electro-thermal-chemical (ETC), electromagnetic (EM), and liquid propellant gun technologies are also major beneficiaries of advanced CFD capabilities.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Domestic Industrial Capabilities

From the industrial base and manufacturing viewpoint, CFD includes the application software and the high-speed processing required to run the software, hardware, and operating systems. Academia and research institutes provide a large portion of the research for developing CFD technology to a point where it can be widely implemented in the defense community. The industrial base issues lie in the computing platforms necessary for CFD. The current platform is the supercomputer, although the development of parallel processing architectures may supplant the supercomputer. (See the sections on Semiconductor Materials and Microelectronics Circuits and Parallel Computer Architectures for an assessment of current supercomputer capabilities.)

2. Projected Industrial Capabilities

In the past, use of CFD has been entirely dependent on the supercomputer and the leadership enjoyed by the United States in CFD is a direct result of the nation's strength in supercomputer technology. Although applications of CFD have been constrained by the capabilities of current generation supercomputers, these limitations may be overcome in the future by parallel processing approaches that will allow greater speed in highly complex computing on less expensive computer systems.

There is also a need to integrate CFD technology and other computational disciplines (e.g., structural mechanics, electromagnetics, optimization) with the manufacturing/production process through a common data base management system. There is an increasing awareness that we must reduce the cost to produce aircraft and marine vehicles in order to be competitive in the world marketplace. Effective integration of design and manufacturing through the use of multidisciplinary computational tools should have a large role to play in reducing the time and the cost of developing such systems.

E. RELATED R&D IN THE UNITED STATES

While some CFD applications (such as hypersonic missiles) are unique to DoD, others (such as aircraft design) have both military and commercial applications, and are supported by NASA and industry. Computational fluid dynamics programs are also extensive in DoE and many universities.

NASA's CFD program is focused on basic research to support the present and future technology needs of the aerospace community. These needs include: (1) developing faster and more efficient numerical algorithms to facilitate solutions of the full Navier–Stokes equations by: large–eddy simulation/small–scale turbulence modeling; (2) developing advanced geometric modeling and grid generation techniques for complex, threedimensional configurations; (3) improving understanding of the effects of grid characteristics on solution accuracy, convergence, and stability; (4) enhancing computational capabilities through development and use of advanced computer architectures and expert systems concepts; and (5) developing improved methods for numerical simulation of aerothermodynamic flow phenomena associated with hypersonic cruise and maneuver vehicles, including real–gas chemistry.

The university community has played an especially active and productive role in CFD research with sponsorship by all three Services, the Defense Advanced Research Projects Agency (DARPA), the Strategic Defense Initiative Office (SDIO), NASA, DoE, and the National Science Foundation (NSF). This capability and knowledge has enormous potential for integration and application to DoD problem solving in military aircraft, missiles, projectiles, ships, submarines, propulsion, and engines. The field is rapidly ad ancing and, as supercomputers become more widely available, this trend is expected to accelerate.

NSF supports research to develop basic algorithms and techniques necessary to compute realistic dynamic fluid flow on a wide range of space and time scales and under many naturally occurring conditions. NSF also provides support for the development of new numerical methods for solving computational fluid dynamics problems and for graphical visualizations with these solutions. Research areas also include engineering studies of turbulence, interface configurations, wakes and wake interactions, and flow–structure interaction. Research is conducted primarily through ongoing programs in engineering, computer science, mathematics, and geosciences (including the National Center for Atmospheric Research).

The US helicopter industry has been slower to utilize CFD technology than the fixed–wing airframe and propulsion communities, but a concerted effort led by DoD and NASA will accelerate the flow of this new capability for improving rotary–wing air mobility and weapons systems. The same applies to ship and submarine design where CFD activities have been accelerated in the 1980s with DoD funds.

F. INTERNATIONAL ASSESSMENTS

1. Technology Base and Industrial Base

Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified through:

- Improved abilities to apply CFD to complex three–dimensional aerothermodynamic analyses (including characterization of chemical reactions)
- Empirically validated codes for three–dimensional analysis of material response to high– strain/high–deformation rates
- Development of algorithms and programming tools to exploit massively parallel computing architectures.

The table on the following page provides a summary comparison of U.S. and other nations for selected key aspects of the technology. The United States is presently the leader in CFD. Cooperative opportunities will exist with NATO countries, especially in the area of specific algorithm developments. Secondary opportunities for cooperation in niche technologies may be realized in a number of countries, including Sweden, Italy, and Israel. Economic and competitive factors will remain important considerations in all these negotiations.

The major European countries have had considerable success in the practical exploitation of CFD. It has been used extensively in Europe to develop better designs for gas turbine engines, transports, business jets, and jet trainers. This capability for exploiting CFD is comparable to methods in the United States. Our European allies have both the expertise in numerical methods and powerful computers.

Much of the basic scientific knowledge related to CFD is known to our allies. The UK is considered to have the greatest experience in applying this knowledge to weapon systems, but Germany, Italy, and France are also assessed to have strong CFD capabilities. The ability of our allies to advance the field of CFD is expected to dramatically improve during the 1990s as the number of supercomputers and the research and development directed toward European involvement with individual national aerospace planes (e.g., the Sanger, Hermes, Hotol, and others) increase.

Knowledge of sophisticated algorithms, as well as the methods for practical exploitation of CFD, is widespread within NATO. France is the pioneer in finite element methods for complex aircraft configurations and is a leader in CFD development for turbulent simulations and modeling. France is probably 2 to 5 years ahead of the United States in large-scale, turbulent eddy modeling, and the Germans have also demonstrated considerable capability toward understanding this fundamental aspect of fluid flow. The UK has efficient methods for transonic flow. Germany is pioneering computations with the full Navier–Stokes equations and is applying them to analysis of hypersonic flight. The Netherlands has an extensive effort in developing algorithms for parallel processing, which also could contribute significantly. Italy is also contributing to the state of the art in CFD.

Japan has supercomputers and, through research in such programs as their aerospace plane, is continuing at a growing rate to develop the validated data bases and sophisticated algorithms required to master CFD. They have recently demonstrated competent efforts in 3–D flow mixing as well as the sophisticated design of 2–D jet engine inlets. Most countries outside of NATO and Japan lack access to large supercomputers to run their computations; however, a number are involved in the development of efficient algorithms.

For example, Sweden is involved in the development of large-scale algorithms. According to some CFD experts, the United States has benefited from these developments. However, Sweden lacks the expertise in large data base management and the data bases themselves to apply CFD technology to state-of-the-art military problems.

Israel has been a pioneer in developing efficient multi-grid methods for a variety of flows but is also limited by the same problems as Sweden. Israel has also demonstrated sophisticated results for simple missile configurations.

China and India have shown interest in CFD, and their capability is growing. All of these countries have traditions of excellence in applied mathematics and fully participate in the science of numerical computation methods. Some capability has also been reported in Australia, but at the present the general capability level for this country is unknown.

The Soviet Union made significant contributions to CFD when it was in its embryonic stage, but they are now assessed to be behind the US in this technology, with the exception of

Summary Comparison — Computational Fluid Dynamics

Selected Elements	USSR	NATO Allies	Japan	Others
To improve abilities to apply CFD to complex 3-D aero-thermodynamic analyses (including characterization of chemical reactions)	□	□□□ +	□□	
Empirically validated codes for 3-D analysis material response to high-strain/high-deformation rates	□	□□□ +	□□	
Development of algorithms and programming tools to exploit massively parallel computing architectures	□	□□	□□	□□ Sweden, Israel □ India, China, Australia
Overall[a]	□	□□□ O	□□	□□ Sweden, Israel □ India, China, Australia

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□ broad technical achievement; allies capable of major contributions

□□□ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions

□□ generally lagging; allies may be capable of contributing in selected areas

□ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators – where significant or important capabilities exist (i.e., 3 or 4 blocks):

+ Foreign capability increasing at a <u>faster</u> rate than the United States

O Foreign capability increasing at a <u>similar</u> rate to the United States

– Foreign capability increasing at a <u>slower</u> rate than the United States algorithm development. They are unlikely to close the gap in the foreseeable future because of US superiority in computers and software. However, the Soviets have a tradition of excellence in mathematical numerical methods. They have been able to keep pace with the United States in areas such as the space program, even with the serious lack of computer power. In CFD, the Soviets have pioneered fractional step methods. Their scientific literature seems to indicate that due to the lack of computational power, Soviet scientists and mathematicians are emphasizing efficient calculation methods to compensate for deficiencies in computer hardware. This could provide a knowledge base for development of efficient algorithms in the future.

2. Exchange Agreements

Formal exchange in CFD is limited, at least in part, by the competitive nature of the field itself. Much of the underlying research into numerical techniques and algorithms takes place in an open academic environment. For practical applications, however, many of the most interesting codes, those that have been empirically validated, are proprietary.

While the Technology Cooperation Program (TTCP) does not appear to have an explicit exchange in CFD, it does provide a number of other mechanisms relating to aircraft control, through which transfers might occur.

The Air Force is the primary proponent for exchanges directly relating to CFD. It has agreements with several of our NATO allies in key areas, and there may be indirect return in this area from a broader international exchange program in computational techniques. In addition, CFD will benefit at least indirectly from many of the exchange programs in propulsion and materials (identified in other sections of this plan).

14. AIR-BREATHING PROPULSION

14. AIR-BREATHING PROPULSION

A. Description of Technology

A dramatic leap in aircraft propulsion capability occurred in the 1940s and 1950s with the introduction and rapid evolution of the gas-turbine engine, and substantial improvements have been made since then. Today, new capabilities in materials and in aerothermodynamic and structural design, together with use of abundant computational capability for control and active stabilization, offer rapid and major advances in propulsion system performance. This rapid evolution will have a tremendous effect on the capability of DoD weapons and platforms, and will have extensive dual-use applications in the US aerospace industrial base, which justifies its selection as a critical technology. Furthermore, the continuing evolution of air-breathing propulsion technology advances in the United States comes at a time when our historic leadership is being challenged by an aggressive international effort.

Generic air-breathing propulsion technology applies to a wide range of military systems, including aircraft, cruise missiles, future hypersonic systems, land combat vehicles, and ships. Types of propulsion systems involved include those based on gas-turbine, ramjet/scramjet, combined cycle, and diesel engines. A broad, aggressive, and well-balanced science and technology effort encompassing further developments in aerothermodynamics, high-temperature/high strength/lightweight materials, structures, tribology, instrumentation, and controls is required to support military requirements and maintain functional superiority against emerging threats.

Within this effort, a specific example of a critical technology program is the Integrated High Performance Turbine Engine Technology (IHPTET) program. This three-phased program is aimed at doubling aircraft gas-turbine propulsion system capability by the turn of the century. The general path to achieving this goal is well known. High temperatures at combustion initiation are required to increase efficiency (or decrease specific fuel consumption) and expand the flight envelope; higher maximum temperatures are required to increase the output per unit airflow; less weight per unit airflow is required to increase the output per unit weight; and all of the preceding requirements must be accomplished while maintaining or increasing internal component efficiency, durability, and life. Specific technology developments required include increased aerothermodynamic design capability for improved component efficiency levels and the control of heat transfer; high-temperature, lightweight materials (higher temperature aluminum and organic matrix composites, titanium and titanium aluminide composites) for the components upstream of combustion initiation; high-temperature materials (ceramic matrix composites, carbon/carbon, intermetallic alloys) for components downstream of combustion; and innovative structural arrangements. All of these developments must be accomplished in an integrated manner for each of the major component areas and for engine configurations as a whole.

The potential use of air-breathing propulsion in the hypersonic regime (Mach 5 to 25) poses a series of new and different problems in aerodynamics, engine design (including unique inlets and nozzle geometries) and propulsion/airframe integration. In addition to the application of IHPTET aerodynamics and materials technologies to hypersonic turbomachinery configurations, technology developments unique to hypersonic air-breathing propulsion include scramjet concepts (utilizing supersonic combustion processes to extend the flight envelope); endothermic fuels and fuel systems to support alternative propulsion approaches in the hypersonic regime; and application/validation of computational methods to analyze the complex, interactive, nonlinear physical phenomena contributing to hypersonic propulsion system behavior.

The critical technology sets for air-breathing propulsion are listed in the following table.

Technology Sets in Air-Breathing Propulsion

IHPTET

- High-pressure ratio, lightweight, actively stabilized compression systems
- High-temperature, improved life combustion systems
- High-efficiency, high-work turbines
- Reduced signature, multi-functional nozzles
- Adaptive, survivable, high-speed integrated control systems
- High-speed, high-temperature mechanical systems
- Operationally realistic, environmentally valid technology demonstrations

Hypersonic Propulsion

- Scramjet/combined cycle technology development/demonstration
- Advanced fuels/systems for hypersonic applications

B. Payoff

1. Impact On Future Weapon Systems

Aircraft gas-turbine technology is pervasive and critical to all current and future air-breathing weapons systems. The size, performance, mission capability, and life cycle cost of aircraft and cruise missile systems are directly dependent on the performance of the propulsion system, as evidenced by the fact that the propulsion system (engines plus fuel) accounts for 40 to 60 percent of the takeoff gross weight for previous, current, and developmental aircraft. In the tightening budgetary environment of the next decade, greater emphasis and dependence will inevitably be placed on upgrading existing and developmental systems with high-payoff engine technologies in lieu of new system development to maintain functional superiority of our weapon systems. (For illustration, since its introduction the F-16 original engine has had three major upgrades, a competitive engine has been introduced, and this latter engine has had a major upgrade!) Given that aircraft-related expenditures in DoD account for approximately one-third of the budget (or roughly $100 billion per year of DoD aircraft-related expenditures), achieving the IHPTET goals will significantly affect future military capability. Accordingly, IHPTET is the highest priority effort in air-breathing propulsion technology. Some specific IHPTET goals and illustrative payoffs are given in the following table.

Goals and Payoffs — IHPTET Program

Application Class	Goals	Payoffs
Fighter/ Attack	• 100% increase in thrust/weight ratio • 40% decrease in fuel burned • Reduced signature	• Sustained Mach 3+ capability • Supersonic V/STOL aircraft • 100% increase in range/loiter/payload over F-14/A-6 • Improved survivability
Rotorcraft	• 40% decrease in specific fuel consumption • 120% increase in power/weight ratio	• 100% increase in range and payload over CH-47
Cruise Missile	• 40% decrease in specific fuel consumption • 100% increase in thrust/unit airflow • Reduced parts count • 60% decrease in cost	• Intercontinental range cruise missiles in size of ALCM • High-speed capability • Improved affordability
Commercial/ Transport	• 30% decrease in fuel consumption • Longer life • Reduced parts count	• Increased range and payload • Longer life • Reduced parts count • Reduced life cycle cost • Improved maintainability

Hypersonic air-breathing propulsion technology has the potential to extend military missions to new flight regimes. Scramjet-/combined-cycle-powered hypersonic aircraft can enhance military capability to project power quickly over great distances; provide high speed, rapid strike capability against time urgent, relocatable targets; make high speed intercepts at short notice; perform timely, quick-reaction reconnaissance; and (through the National Aerospace Plane (NASP) program) may ultimately provide more economical and timely access to space. Accordingly, hypersonic propulsion is the second highest priority effort in air-breathing propulsion technology. Some specific goals and payoffs are shown in the following table.

Goals and Payoffs — Hypersonic Proplsion

Application Class	Goals	Payoffs
Hypersonic aircraft	• Cryogenic hydrogen hypersonic propulsion system (NASP) • SL to Mach 5+ combined cycle engine operation on hydrocarbon fuels • 2000°F storable endothermic hydrocarbon fuels	• Single-stage-to-orbit • Mach 10 cruise with cryogenic hydrogen • Mach 5+ cruise with hydrocarbon fuels • Enhanced vehicle responsiveness, effectiveness, and survivability

2. Potential Benefits to the industrial base

Aircraft gas-turbine technology is vital to the U.S. industrial base. The value of military and commercial shipments for the domestic aircraft gas-turbine manufacturers (including uninstalled engines, installed engines, and parts) was approximately $21.6 billion in 1988. These shipments represent almost 20 percent of the total aerospace industry business for 1988, which itself accounts for over 4 percent of the 1988 total manufacturing business of the United States. By virtue of the aircraft gas turbine's importance in determining the overall quality of aircraft, it is a major factor in the current favorable balance of trade in the aerospace sector, and the United States continues to be preeminent in this area. However, like the current US engine production share which has declined from 84 percent in 1970 to 62 percent in 1988, this advantage has been eroding since the early 1970s. At its current rate of loss (~1.5 percent per year), the United States will sink to trade deficit status by the end of the decade unless we change the fundamental trend. Because aircraft gas-turbine technology generally is equally applicable to military and civil engines (particularly for the High-Speed Civil Transport), achieving the IHPTET goals will ensure that US engines are produced with superior quality and performance at lower cost than can be achieved by any of our international competitors, thus assuring continued US preeminence well into the 21st century. Further, aircraft gas-turbine technology is applied to ship propulsion, tank propulsion, and stationary power generating stations.

Hypersonic propulsion technology can also apply to high speed transports. Advancements in materials and aerothermodynamic techniques can be expected to contribute significantly to a wide spectrum of the military and commercial industrial base.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Compression Systems

(1) Objectives

The overall objective is to apply advancements in aerodynamics; three-dimensional viscous computational fluid dynamics (CFD); active system stabilization; critical-path high strength/weight materials [such as titanium aluminides (TiAl and Ti_3Al), metal matrix composites (MMC), and composite materials]; and innovative structural designs to axial, centrifugal, mixed flow, and advanced concept compression/internal flow systems. The overarching goal is to achieve the following phased IHPTET component performance payoffs for turbofan/turbojet (TF/TJ), turboshaft/turboprop (TS/TP), and expendable (EXP) classes of engine:

	Phase I (FY 1991)	Phase II (FY 1997)	Phase III (FY03)
TF/TJ			
Polytropic efficiency	+3%	+4%	+5%
Stage loading	+20%	+30%	+50%
Component weight	-25%	-40%	-50%
Compressor exit temperature	+100°F	+200°F	+400°F
TS/TP			
Polytropic efficiency	—	+2%	+3%
Overall pressure ratio	+30%	+100%	+150%
Compressor exit temperature	+100°F	+300°F	+500°F
Stage loading	—	+30%	+110%
EXP			
Polytropic efficiency	—	+2%	—
Compressor exit temperature	+200°F	+300°F	+500°F
Cost	—	-5%	-10%

(2) Development Milestones

TF/TJ: A major emphasis is on the successive introduction of critical path materials to both rotating and static components in order to achieve the temperature, performance, and weight goals.

- Ti_3Al aft rotor (FY 1992).
- High speed brush seals (FY 1992).
- TiAl metal matrix composite (MMC) rotor (FY 1993).
- Enhanced flow compressor (FY 1994).
- High temperature shrouds/low-leakage seals (FY 1995).
- Lightweight fan attachment (FY 1996).
- Hollow MMC fan/all MMC compressor (FY 1996).

TS/TP: Spinoff TF/TJ developments in aerodynamics and critical-path materials will be coupled with high-temperature seals technology and applied to both small (<2500 shp) and large (2500–15000 shp) TS/TP systems to achieve high overall cycle pressure ratios at high levels of efficiency (η) and stall margin.

- High-efficiency/pressure ratio compressor (FY 1994).
- Hyper-bowed stators (FY 1994).
- +30 percent stage loading axial/centrifugal compressor (FY 1995).
- Dual alloy MMC impeller (FY 1996).
- High stage-loading mixed flow rotor (FY 1996).

EXP: High-risk/high-payoff technologies are demonstrated early in non-man-rated (limited life) compression systems.

- Non-metallic structure (FY 1992).
- Mixed-flow rear stage (FY 1994).
- +2 percent η axial/centrifugal compressor (FY 1995).

b. Combustion Systems

(1) Objective

The overall objective is using advanced, high-temperature ceramic and ceramic matrix composites (CMC), titanium aluminide metal matrix composites (MMC), innovative high-temperature fuel injection concepts, transpiration cooling concepts, and integrated diffuser/combustor case and augmentor liner/nozzle designs to satisfy the goal of achieving the following phased IHPTET component performance payoffs for turbofan/turbojet (TF/TJ), turboshaft/turboprop (TS/TP), and expendable (EXP) classes of engine:

	Phase I (FY 1991)	Phase II (FY 1997)	Phase III (FY03)
TF/TJ			
Combustors			
Turbine inlet temperature	+400°F	+600°F	+900°F
Heat release rate	+10%	+20%	+30%
Turn-down ratio	+50%	+75%	+100%
Pattern factor	0.25	0.15	0.10
Augmentors			
Augmentation ratio	+10%	+20%	+30%
Dry pressure loss	-30%	-50%	-75%
Efficiency	+5%	+8%	+10%
TS/TP			
Heat release rate	+40%	+60%	+70%
Ignition fuel/air ratio	-25%	-40%	-60%
Length/diameter ratio	-10%	-20%	-30%
Pressure loss	-10%	-30%	-50%
EXP			
Subsonic			
Combustor exit temperature	+300°F	+500°F	+700°F
Pattern factor	0.25	0.20	0.15
Fuel	JP-10	JP-10/RJ6	JP-10/RJ6
Supersonic			
Combustor exit temperature	+700°F	+1200°F	+1700°F
Heat release rate	+50%	+150%	+300%
Fuel	JP-10	JP-10/RJ6	Endothermic

(2) Development Milestones

TF/TJ: Focus is on developing and demonstrating transpiration-cooled augmentor liners, integrated augmentor/nozzle concepts, and integrated MMC diffuser/combustor case concepts for TF/TJ systems.

- 2800°F ceramic liner (FY 1992).
- High shear fuel injector (FY 1994).

- Integrated augmentor/nozzle (FY 1993).
- Integrated vane/diffuser/combustor (FY 1995).
- Uncooled combustor design (FY 1997).

TS/TP: Achieving high heat release rates and application of critical-path materials are the focus of technology development efforts in this class of engines.

- Small, ΔT combustor (FY 1992).
- Compliant matrix liner (FY 1993).
- 2400°F CMC combustor (FY 1994).
- Circumferential fuel injector (FY 1997).

EXP: Efforts focus on early demonstration of materials technology to reduce cooling requirements and achieving high heat release rates to reduce combustor volume.

- High heat-release-rate combustor (FY 1994).
- Reduced-volume, non-metal combustor (FY 1995).
- 2800°F CMC combustor (FY 1996).
- Carbon-carbon liner (FY 1997).

c. **Turbine Systems**

(1) Objective

The overall objective is using three-dimensional viscous computational fluid dynamics (CFD) codes, innovative cooling concepts, improved thermal barrier coatings, high temperature intermetallic materials, and advanced non-metal/composite materials to achieve the following phased IHPTET component performance payoffs for turbofan/turbojet (TF/TJ), turboshaft/turboprop (TS/TP), and expendable (EXP) classes of engine:

	Phase I (FY 1991)	Phase II (FY 1997)	Phase III (FY03)
TF/TJ			
Stage work	+20%	+30%	+50%
Turbine inlet temperature	+300°F	+600°F	+900°F
Efficiency	+1%	+2%	+3%
Cooling flow	-10%	-35%	-60%
TS/TP			
Stage work	+20%	+30%	+50%
Turbine inlet temperature (small/large engines)	+200/300°F	+400/600°F	+700/1100°F
Efficiency	+1%	+2%	+3%
Cooling flow	-10%	-35%	-60%
EXP			
Stage work	+20%	+30%	+50%
Turbine inlet temperature (uncooled/cooled)	+500/1400°F	+900/1500°F	+1400/1700°F
Efficiency	+1%	+2%	+3%
Cooling flow	-10%	-35%	-60%

(2) Development Milestones

TF/TJ: Emphasis is on increasing critical-path cooling effectiveness to reduce cooling flows, reducing leakage losses, utilizing highly loaded/counter-rotating turbine designs to reduce the number of stages, and applying high temperature materials to reduce turbine cooling requirements and component weight.

- High cooling effectiveness (FY 1993).
- High-temperature brush seals/shrouds (FY 1995).
- Fiber-reinforced disk (FY 1993).
- Lightweight intermetallics (FY 1995).
- Low cooling HPT (FY 1995).
- Composite frames and cases (FY 1997).

TS/TP: Critical-path technologies include developing and demonstrating high levels of cooling effectiveness for small blade designs, small blade manufacturing concepts, and application of non-metallics in uncooled airfoils.

- High work, low cooling flow turbine (FY 1993).
- Small, high work turbine (FY 199).
- Ceramic mixed flow turbine (FY 1994).
- Cooled radial turbine (FY 1995

EXP: Focus is on applying high-temperature ceramic matrix composite materials technology to rotating components, utilizing innovative cooling concepts, and incorporating high-speed bearing technology.

- High-temperature CMC/C-C materials (FY 1993).
- High-speed, C-C rotor (FY 1995).
- Uncooled CMC rotor (FY 1996).

d. Exhaust Nozzles

(1) Objectives

The overall objective is using advanced materials (such as carbon-carbon, titanium aluminide, and ceramic matrix composites) to provide reduced-weight, multi-function exhaust nozzles with higher system performance and aggressive balanced signature levels for enhanced survivability (S/V) with the goal of achieving the following phased IHPTET component performance payoffs for turbofan/turbojet (TF/TJ) and expendable (EXP) classes of engine:

	Phase I (FY 1991)	Phase II (FY 1997)	Phase III (FY03)
TF/TJ			
Maximum A/B cooling flow	-10%	-50%	Uncooled
Leakage	-10%	-25%	-50%
S/V weight penalty	-10%	-35%	-60%
Nozzle weight	-10%	-25%	-50%
EXP			
Volume		-5%	-5%
S/V weight penalty	-10%	-25%	-50%
Nozzle weight	-5%	-10%	-25%

(2) Development Milestones

TF/TJ: Emphasis is on addressing manufacturing issues for advanced nozzle configurations, identifying the effects of obtrusive inlet/engine interface configurations on performance, developing selective cooling methods, and demonstrating advanced materials/ structural designs in a realistic environment.

- Spherical convergent flap nozzle demo (FY 1992).
- 2-D pitch/yaw nozzle (FY 1993).
- Titanium aluminide/MMC structure (FY 1994).
- High-temperature CMC panels (FY 1994).
- Full vectoring demo (FY 1997).

TS/TP: Nozzle technology does not play a major role in the turboshaft/turboprop class of engines.

EXP: Focus is on applying advanced oxide-based ceramics for survivability/performance enhancement, demonstrating advanced structural materials, and integrating survivability into the front and rear end rotating and static components.

- Inlet/nozzle concepts (FY 1992).
- High temperature ceramic matrix composites (FY 1993).
- Advanced ceramic matrix exhaust system design (FY 1994).
- Pitch/yaw vectoring demo (FY 1996).
- Uncooled, balanced S/V design (FY 1997).

e. **Controls/Accessories**

(1) Objective

The overall objective is to apply lightweight materials, high-temperature electronics, integrated flight/propulsion control architecture, performance-seeking control logic, and optical communication technology to achieve the following phased IHPTET component performance payoffs for turbofan/turbojet (TF/TJ), turboshaft/turboprop (TS/TP), and expendable (EXP) classes of engine:

	Phase I (FY 1991)	Phase II (FY 1997)	Phase III (FY03)
TF/TJ			
Environmental temperature	+100°F	+250°F	+400°F
Control/accessories weight	-20%	-35%	-50%
TS/TP			
Environmental temperature	+50°F	+150°F	+200°F
Control/accessories weight	-20%	-35%	-50%
EXP			
Environmental temperature	+200°F	+400°F	+600°F
Control/accessories weight	-20%	-35%	-50%
Control system cost	-30%	-50%	-60%

(2) Development Milestones

TF/TJ: Early focus is on investigating advanced simulation technology for engine controls (ASTEC) to exploit increases in computational power, and on developing/demonstrating performance-seeking optimization logic for highly integrated digital controls. Emphasis is also on using lightweight/high-temperature materials, fiber optic communication technology, and high-temperature electronics to reduce weight, increase performance, and extend engine durability/life levels.

- ASTEC (FY 1992).
- 700°F electronics (FY 1992).
- Fiber optics sensors/integration (FY 1994).
- Lightweight nozzle actuator (FY 1995).

- Full authority opto-electronic control (FY 1996).

TS/TP: Emphasis is on the progressive application of composites and high-temperature aluminums to engine pumps and control unit housings, opto-electronic sensors, high-temperature electronics, and flexible control logic.

- EMI/EMP insensitive control (FY 1993).
- High-temperature OMC (FY 1994).
- Reconfigurable control (FY 1995).

EXP: Focus is on developing thermal management approaches for controlling heat load and infrared suppression, and providing nuclear radiation/corrosive environment survivability.

- High-performance fuel pump (FY 1993).
- High-temperature aluminum/OMC (FY 1994).
- Exotic fuel (endothermic/cryogenic/multiphase) pumping system (FY 1995).

f. Mechanical Systems

(1) Objectives

The overall objective is applying high-temperature lubricant technology, composite materials, innovative magnetic and dry lube bearing concepts, and advanced fabrication techniques to achieve the following phased IHPTET component performance payoffs for turbofan/turbojet (TF/TJ), turboshaft/turboprop (TS/TP), and expendable (EXP) classes of engine:

	Phase I (FY 1991)	Phase II (FY 1997)	Phase III (FY03)
TF/TJ			
Liquid lubrication temperature	+50°F	+250°F	+400°F
Solid lubrication temperature	Base	+400°F	+900°F
Bearing speed	+10%	+20%	+40%
Intershaft seal velocity	+15%	+70%	+85%
Conventional seal velocity	+15%	+35%	+50%
Lubrication system weight	-5%	-10%	-20%
TS/TP			
Same as TF/TJ			
EXP			
Solid lubrication temperature	Base	+500°F	+800°F
Lubrication system weight	-5%	-20%	-50%

(2) Development Milestones

TF/TJ: Emphasis is on base fluid and additive research, tribological properties investigations, development of candidate formulations, seal material development, application of high-temperature component materials, and sub-scale/full-scale component test and evaluation.

- Active damper (FY 1992).
- High-speed (1200 FPS) air/oil seal (FY 1993).
- Hybrid tapered roller bearing (FY 1994).
- 1200 FPS counter-rotating intershaft seal (FY 1994).
- 600°F PFE lube (FY 1995).
- High-temperature/all-ceramic hybrid bearing (FY 1995).
- 800°F lube research (FY 1996).
- High-efficiency magnetic bearing (FY 1997).

TS/TP: TF/TJ and TS/TP activities are complementary and are addressed in the TF/TJ section above.

EXP: Emphasis is on solid lubricant technology development/validation and ceramic bearing development.

- Solid lube hybrid bearing (FY 1992).
- Ceramic roller bearing (FY 1993).
- High-temperature load damper (FY 1994).
- Fluoride-based solid lube (FY 1995).
- 1800°F solid lube validation (FY 1997).

g. **Technology Demonstrators**

(1) Objectives

Technology demonstrators have two objectives. The first is evaluating integrated behavior in a realistic engine environment. This evaluation is used to guide the further development of component technology. The second is validating that the technology is sufficiently developed and understood to be transferred to new engine developments and to improvements of existing engines. The IHPTET program is structured so that these technology readiness demonstrations are performed competitively in each of the three demonstrator classes in each of the three phases. The specific objectives for each class of demonstrator (turbofan/turbojet, turboshaft/turboprop, and expendable) are shown below.

TF/TJ: Demonstrate the following phased IHPTET core engine gas generator (high pressure compressor, combustor, and low pressure turbine) and full engine performance goals in the Advanced Turbine Engine Gas Generator (ATEGG), and Joint Technology Demonstrator Engine (JTDE) programs:

	Phase I (FY 1991)	Phase II (FY 1997)	Phase III (FY03)
Core Engines (ATEGG)			
Maximum turbine inlet temperature	+300°F	+600°F	+900°F
Total cooling air	-10%	-35%	-60%
Full Engines (JTDE)			
Thrust-to-weight ratio	+30%	+60%	+100%
Compressor exit temperature	+100°F	+200°F	+400°F
Fuel burned	-20%	-30%	-40%

TS/TP: Demonstrate the following phased IHPTET performance goals for subsonic applications in the Joint Turbine Advanced Gas Generator (JTAGG) program:

	Phase I (FY 1991)	Phase II (FY 1997)	Phase III (FY03)
JTAGG			
Horsepower/weight	+40%	+80%	+120%
Specific power	+50%	+80%	+100%
Specific fuel consumption	-20%	-30%	-40%
Turbine inlet temperature	+300°F	+600°F	+1000°F
Compressor exit temperature	Base	+200°F	+400°F

EXP: Provide early verification of high risk/high payoff materials technologies and demonstrate the following phased IHPTET performance goals for non-man-rated (limited life) applications in the Joint Expendable Turbine Engine Concepts (JETEC) program:

	Phase I (FY 1992)	Phase II (FY 1999)	Phase III (FY05)
JETEC			
Compressor exit temperature	+200°F	+300°F	+500°F
Maximum turbine inlet temperature	+500°F	+900°F	+1400°F
Specific fuel consumption	-20%	-30%	-40%
Specific thrust	+35%	+70%	+100%
Cost	-30%	-45%	-60%

(2) Development Milestones

Core Engines: ATEGG emphasis is on integrating and demonstrating core engine materials and aeromechanical technologies, including a high temperature titanium aluminide MMC compressor, an integrated vane/diffuser/combustor, high speed (1200 FPS) seals, fiber reinforced turbine disks, and high temperature hybrid bearings by the end of FY 1996 to validate the IHPTET Phase II goals.

Full Engines: JTDE emphasis is on integrating the ATEGG core with hollow metal matrix composite fans, uncooled low pressure turbines, composite frames and cases, yaw vectoring nozzles, and full authority opto-electronic controls and demonstrating the IHPTET Phase II goals by the end of FY 1997.

JTAGG: Emphasis is on demonstrating component technologies applicable to a broad spectrum of subsonic engines in both the smaller (less than 2500 horsepower) and larger (from 2500 to 15000 horsepower and up to 15000 lbs thrust) classes. Sequential JTAGG tests demonstrate swept aero compressors, advanced materials (such as high–temperature titanium, ceramics, metal matrix composites, and ceramic matrix composites), thermal barrier coatings, low–leakage/high–speed seals, high–temperature lubricants, and optical control methods to demonstrate the IHPTET Phase II system performance goals by the end of FY 1997.

JETEC: Emphasis is on integrating and testing critical–path materials such as high–temperature (2800°F) ceramic matrix composites and carbon–carbon (in the combustor, turbine, and exhaust nozzle); high–temperature solid lubricants; high heat release rate combustors; air journal bearings; and low–cost static structures to demonstrate the IHPTET Phase II system performance goals by the end of FY 1997.

h. Scramjet/Combined Cycle Systems

(1) Objectives

The overall objectives for scramjet technology are: (1) developing of a cryogenic–hydrogen–fueled engine for single–stage–to–orbit or sustained cruise at Mach 10 capability and (2) demonstrating a storable–hydrocarbon–fueled engine with combustion efficiencies of greater than 95 percent for applications up to Mach 8. Objectives for combined–cycle technology include demonstrating engine operation from sea level static to Mach 5+, including mode change transition in the Mach 3 to 4 range.

(2) Development Milestones

Scramjet: Emphasis is on developing a cryogenic–fueled scramjet engine and developing hydrocarbon–fueled scramjet combustor concepts which eliminate the need for highly reactive, non–storable combustion aids to sustain scramjet operation.

- Scramjet flow–path performance demonstration to Mach 8 (NASP) (FY 1993).
- Scramjet engine materials demonstration (NASP) (FY 1993).
- Wide Mach range combustor demonstration (FY 1994).
- Scramjet performance demonstration to Mach 8 (NASP) (FY 1995).
- Improved efficiency combustor demonstration (FY 1996).

Combined Cycle: Advancing ramburner technology, aerodynamics, and innovative compression concepts, coupled with developing high–temperature fuels, offer the potential for increases of 100 percent in specific impulse and 22 percent in engine thrust–to–weight.

- Wide Mach ramburner demonstration (FY 1993).
- Transition valve demonstration (FY 1994).
- Turboramjet (TRJ), Air–turborocket (ATR) (both liquid and solid fueled) (FY 1995).

i. **Advanced Hydrocarbon Fuels/Systems**

(1) Objectives

The overall objectives are the development of high–temperature, thermally–stable JP fuels and fuel system components capable of achieving the following performance gains compared to current JP fuels:

Fuel temperature	:	+575°F
Heat sink	:	+500%

(2) Development Milestones

Emphasis is on increasing the thermal stability limit of current JP–8 fuel at the main burner by 100°F and the available fuel heat sink by 50 percent, while working on revolutionary approaches for a new hydrocarbon fuel (JP–900) which offers the potential of a 575°F increase in fuel temperature and a 500 percent increase in heat sink.

- Heat sink demonstration on JP–8 (FY 1994).
- Fuel qualification (FY 1997).

2. **Technology Objectives**

At the core of the air–breathing propulsion program are the IHPTET efforts which are aimed at satisfying the fundamental performance needs of the aircraft gas turbine engine. This program is structured in three time–phased steps, aimed at demonstrating technology in experimental engine configurations for three classes of engines: man–rated turbofan/turbojet, man–rated turboshaft/prop, and expendable engines for cruise missile or unmanned air vehicle applications. To achieve the overall demonstration goals, technology developments are needed in six major component areas: compression systems, combustion systems, turbine systems, nozzles, controls/accessories, and mechanical systems. The IHPTET technology objectives for these six component areas, as well as the technology demonstrators, are shown in the table on the following page. Roadmaps for achieving these milestones are shown in Appendix A. The goals are referenced to the state–of–the–art in 1987 and are to be achieved while maintaining current engine life and durability.

To achieve the overall hypersonic propulsion goals, efforts are focused in two areas: (1) scramjet/combined cycle systems and (2) advanced hydrocarbon fuels/systems. The primary contributor to the development of hypersonic propulsion technology is the NASP program. Milestones for these two areas are shown in the following table.

Technology Objectives — IHPTET Program

Technology Set	By 1991 (Phase I)	By 1997 (Phase II)	By 2003 (Phase III)
Compression systems	• Metal matrix composites • Swept aerodynamics • 1300°F titanium/titanium aluminide • Hollow blades	• 1500°F titanium aluminide/ MMC • Brush seals • Fiber-reinforced MMC ring rotors • 3-D viscous CFD design	• 1800°F titanium aluminide/ MMC • All composite design • Exoskeletal structure • Max loading • Active stabilization
Combustion systems	• Double dome/double wall liners • Transpiration cooled augmentor liner • 2200°F ceramics • High-temperature augmentor flameholder spraybar	• Innovative dome concepts • CMC augmentor liner • 2400°F ceramics • Integrated augmentor/nozzle • Variable geometry fuel nozzles	• Variable geometry flow configuration • Integral design • Non-metallic liners • Titanium MMC cases • Active combustion control
Turbine systems	• High-effectiveness cooling • 1850°F disk superalloy • High AN^2 rotors • Ceramic blade outer air seals • 2100°F thermal barrier coatings	• Improved cooling effectiveness • 3-D viscous CFD design • 2000°F intermetallics • Fiber-reinforced disk • 2500°F uncooled non-metallics • 2500°F thermal barrier coatings	• 2800°F cooled non-metallics • 2600°F intermetallics • Composite cases • Air leakage reduced 50% • Lightweight static structures
Exhaust nozzles	• Pitch vectoring • Composite liners • Selective cooling • 25-2800°F C-C structures	• Pitch/yaw vectoring • Titanium aluminide MMC structures • Reduced cooling • 2800°F CMC panels	• Full vectoring • All-composite uncooled design • 1800°F titanium aluminide MMC • Greater than 2800°F CMC/C-C
Mechanical systems	• 400°F liquid/600°F solid lube • Intershaft bearings/seals • Advanced dampers • 1000°F limited life bearing	• 600°F liquid lube • Advanced bearing/seal/ gear materials • Advanced analytical tools • 1500°F limited life bearing	• 700-800°F liquid lube • Advanced component materials • Integrated mechanical system demonstration • High modulus shafting

Technology Objectives — IHPTET Program (Continued)

Technology Set	By 1991 (Phase I)	By 1997 (Phase II)	By 2003 (Phase III)
Technology Demonstrator (turbofan/ turbojet)	• +30% thrust/weight • +300°F turbine inlet temperature • +100°F compressor discharge temperature • -20% fuel burned	• +60% thrust/weight • +600°F turbine inlet temperature • +200°F compressor discharge temperature • -30% fuel burned	• +100% thrust/weight • +900°F turbine inlet temperature • +400°F compressor discharge temperature • -40% fuel burned
Technology Demonstrator (turboshaft/ turboprop)	• -20% SFC • +40% power/weight • +300°F turbine inlet temperature	• -30% SFC • +80% power/weight • +600°F turbine inlet temperature	• -40% SFC • +1200% power/weight • +1000°F turbine inlet temperature
Technology Demonstrator (expendable)	• -20% SFC • +35% thrust/airflow • -30% cost • 1100°F combustor inlet temperature	• -30% SFC • +70% thrust/airflow • -45% cost • 1200°F combustor inlet temperature	• -40% SFC • +100% thrust/airflow • -60% cost • 1400°F combustor inlet temperature

Technology Objectives — Hypersonic Propulsion

Technology Set	By 1992 (Phase I)	By 1999 (Phase II)	By 2005 (Phase III)
Scramjet/combined cycle systems	• Simulated low speed performance (NASP) • Scramjet performance demonstrated (NASP) • Wide Mach combustor demonstration (missile) • Improved efficiency combustor (missile) • 1400°F hydrocarbon fuel heat exchanger (TRJ) • 2140°F integrated ramburner spraybar/flameholder (TRJ) • Transition valve mode change demonstration (TRJ) • 2000°F CMC fan (ATR)	• Single-stage-to-orbit demonstration (NASP) • Solid fuel piloting concept (missile) • Variable geometry ramburner (TRJ) • Mach 5 freejet engine demonstration (ATR) • Improved mixer concept (ATR) • High temperature uncooled turbine (ATR) • Improved high efficiency combustor concept (ATR)	• Mach 7+ freejet liquid fueled engine demonstration (missile) • Solid fuel propellant development (missisle) • 2000°F fuel heat exchanger/ reactor (TRJ/ATR) • Advanced ramburner fuel injector/flameholder (TRJ) • Dual mode turboscramjet burner Mach 7+ operation (TRJ) • 2500°F fan (ATR) • 800 sec ISP solid fuel engine demonstration (ATR) • High energy density solid gas generator propellant (ATR)
Advanced hydrocarbon fuels/systems	• Advanced JP-8	• 2250 BTU/lbm cooling with JP fuel • Advanced fuel system demonstration	• 3000 BTU/lbm cooling with JP 900

3. Resources

DoD funding for developing IHPTET and hypersonic propulsion technology is as follows:

Funding — Air-Breathing Propulsion ($M)

FY87–91	FY92	FY93	FY94	FY95	FY96	FY97
958	224	211	185	190	193	201

4. Utilizing the Technology

The primary customers of the technology developed and demonstrated under the three-phased IHPTET initiative and the hypersonic initiative are the Military Departments, which will: (1) upgrade the performance and/or life of existing engines to enhance current system capability (e.g., upgrades to the F100, F110, and F404 engines for the F-14, F-15, F-16, and F-18); (2) improve and subsequently upgrade engines currently in development (for example, the technology demonstrated is directly applicable to the F119 and F120 for the ATF); (3) provide a basis for new engine developments currently in the conceptual stage (such as engines for a short-take-off-and-vertical-landing aircraft, an advanced tactical transport, and future high Mach vehicles). An important secondary user of this technology is the commercial aircraft industry, since to a large extent the technology for military engines is common to commercial engines.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

Capabilities in the United States for manufacturing current production gas turbine engines are excellent, with the possible exception of bearings. Current capabilities include the production of aluminum, titanium, and nickel- or cobalt-based superalloys (including the production of powders); hot isostatic pressing; hot isothermal forging; inertia welding; diffusion bonding; precision casting of air-cooled turbine parts in single-crystal, directionally solidified, or equiaxed forms; electrochemical and electrical discharge machining; electron-beam welding; laser drilling and welding; and all needed types of coatings.

Many of the current manufacturing process capabilities must be significantly enhanced in the near term if the United States is to maintain its lead in propulsion technologies and meet the air-breathing propulsion goals of the future. Super plastic forming/diffusion bonding (SPF/DB), for example, is still being developed for large-scale, high-volume manufacture of critical structures and components. Significant additional technology and process control efforts are required to achieve high performance, cost effective SPF/DB hardware. Similarly, coating applications for hot section components and fabrication techniques for advanced structures (e.g., thrust vectoring exhaust nozzles) need to be included as part of any manufacturing technology and process plans.

Other areas which require significant manufacturing technology initiatives to address near and longer term propulsion objectives include: (1) casting net shape components produced from advanced high temperature and titanium alloys, (2) coatings for both engine components and in-process materials, (3) non-destructive evaluation (NDE) techniques to meet design life goals and improve process control, (4) joining techniques for dissimilar advanced materials, and (5) fabrication techniques for the affordable production of metal and ceramic matrix composites.

2. Projected Industrial Capabilities

Achievement of the air-breathing propulsion goals will require that new manufacturing capabilities be developed. These new capabilities will include the manufacture of various fibers for composite materials with titanium, aluminum, titanium aluminide, ceramic, carbon, and intermetallic matrices; the manufacture of the associated composite materials in near-net-shape form; the production of rapidly solidified alloys; greater precision in the casting of air-cooled, single-crystal parts; durable coatings for carbon/carbon composites; high-strength bonding techniques; and greater precision in machining methods.

Developing the needed processing capabilities on a laboratory scale is an integral part of the aircraft propulsion initiative, since developing the capability independently from the component to which it is to be applied is generally not possible. Engine manufacturers and materials suppliers participate, often jointly, in both DoD-sponsored and industry-sponsored programs to develop the needed processing activities. Subsequent to the development of these capabilities on a laboratory scale, manufacturing technology programs will be initiated to transfer the technology development efforts to needed production capabilities. Although the IHPTET initiative is actively addressing design and manufacturing relationships to ensure producibility of a manufacturable design, increased emphasis is needed in MANTECH to produce the materials and parts.

E. RELATED R&D IN THE UNITED STATES

Both NASA and industry participate in the coordinated IHPTET program. For FY 1991, related NASA activity is primarily directed at discipline research in high-temperature, lightweight materials and experimental and analytical internal fluid mechanics. NASA's materials research includes metallic/intermetallic matrix composites and ceramic matrix composites. Internal fluid mechanics research includes the development and experimental verification of advanced three-dimensional viscous codes for application to ducts, turbomachinery, and combustors. Additional research activities for hypersonic propulsion is handled principally by NASA at its Langley, Ames, and Lewis Research Centers. NASA's hypersonic research is focused on the fundamental flow mechanisms in scramjet engines such as high-speed mixing and combustion, combustor integration with the inlet and nozzle, and development and verification of advanced computational codes for high speed reacting flows.

For FY 1992, related NASA IHPTET funding is approximately $33 million, and related industry discretionary funding is estimated to be approximately $125 million. (DoD-requested IHPTET funding is $131 million). Additional research activities for hypersonic propulsion are handled principally by the Air Force and NASA (at its Langley, Ames, and Lewis Research Centers). Although not a participant in IHPTET, DoE's materials expertise also contributes to the national technology base, and NSF supports engineering research on chemical kinetics of combustion and high-temperature combustors. NIST sponsors a research program in laser-induced flourescence for temperature measurements in combustion systems.

Both DoD and NASA support academic research activities on airbreathing propulsion at a few key universities. While small in financial terms, these programs are of key importance, as sources of well educated personnel knowledgeable about air breathing propulsion, for enhancement of the fundamental technology base, and as a source of fresh ideas.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Although the two priority efforts in air-breathing propulsion, IHPTET and hypersonic propulsion, are different in form, many key aspects of the technology are similar. Research and development in the following four areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Development and design integration of lightweight, high-temperature, high-strength materials
- Reduction of observables in high temperature air-breathing propulsion systems
- Modeling and simulation (including CFD) of complex aerothermodynamic flow and empirically calibrated data bases
- Development of scramjet/combined cycle propulsion.

The table on the following page provides a summary comparison of U.S. and other nations, funding for selected aspects of propulsion technology. With regard to the aircraft gas turbine engine (GTE), the U.S. continues to be the preeminent manufacturer, but less so than in the past as measured by market share. (U.S. market share has dropped from 84 percent to 62 percent over the past 20 years.) Since industry financial support for U.S. technology development is derived from military and commercial sales, a strong U.S. market share is important to the health of the U.S. GTE technology base.

With regard to hypersonic propulsion, support has been insufficient for many years to establish and maintain a strong US industrial base. The current base is weak and diffused. Foreign investment in these technologies is increasing and will eventually relegate the United States to a second or third place status unless urgent remedial action is taken.

In general, the U.S. continues to lead in the key aspects of GTE technology. Principal cooperative opportunities could exist with NATO countries (especially with France, Germany, and the UK) and with Japan in both the GTE and hypersonic propulsion arenas. In order to capitalize on the benefits of cooperative technology development, it is necessary that subsequent co-development collaborations favor future U.S. market share.

The NATO infrastructure for gas turbine engine development and production is highly developed. Increasing cooperation among the European Community (EC) nations (principally the UK, France, Germany, and Italy) in aircraft engines should permit them to field a complete range of high technology aircraft engines for military applications. French high-thrust commercial turbofan engines are based on a joint venture with a U.S. manufacturer, in which the low pressure/temperature components are made in France. In addition, France has emerged as a leading supplier of critical ceramic composites being investigated for potential use in jet engine hot sections. These are being evaluated in the U.S. IHPTET program. U.S. aircraft engine builders have also entered into development and manufacturing agreements with other EC engine producers.

Summary Comparison — Air-Breathing Propulsion

Selected Elements	USSR	NATO Allies	Japan	Others
Development and design integration of lightweight/ high temperature/high strength materials	□□	□□□ ○	□□□ +	
Reduction of observables in high temperature air-breathing propulsion systems	□□	□□□ ○	□□□ −	
Modeling and simulation, and empirically calibrated databases therefor	□	□□	□□	
Development of Scramjet propulsion	□□□ ○	□□	□□	
Overall[a]	□□	□□□ ○	□□	

[a] The overall evaluationi s a subjective assessment of the average standing of the technology int he nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

- □□□□ broad technical achievement; allies capable of major contributions
- □□□ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
- □□ generally lagging; allies may be capable of contributing in selected areas
- □ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators – where significant or important capabilities exist (i.e., 3 or 4 blocks):

- \+ Foreign capability increasing at a faster rate than the United States
- ○ Foreign capability increasing at a similar rate to the United States
- − Foreign capability increasing at a slower rate than the United States

While the U.S. IHPTET project still is at the leading edge of technology, in the near term European consortia will have the capability to compete effectively at the state of the art. The European helicopter and fighter programs are providing a base for continued research and development in this area.

Other countries that have significant development programs include Israel, Sweden, India, Taiwan, and the PRC. These programs are not, however, considered leading candidates to contribute to significant advances beyond existing NATO capabilities.

Foreign activity in the area of hydrogen-fueled scramjets is not assessed as comparable to the US level of activity for the NASP program. However, France is about to launch a major effort to develop scramjet technologies and both Japan and Germany have initiated hypersonic aircraft programs.

France is now the international leader in missile ramjet propulsion in the free world and has an aggressive program to extend hydrocarbon-fueled, high-speed, air-launched weapon technology. We anticipate that France will also have a significant capability in both the hydrogen-fueled scramjet and combined cycle engine arenas in the near future as a result of a joint venture agreement between SNECMA and SEP (called HYPERSPACE). French high-temperature materials capability is also outstanding.

Germany is the only free world country actively addressing a hypersonic air-breathing first-stage space launcher (the SANGER Project). This funded effort has led to the development of a hydrogen-fueled conventional ramjet and a corresponding turboramjet program. To provide early proof of the air-breathing propulsion concept, a manned experimental vehicle will be flown (called HYTEX) before the year 2000. The German program is eliciting interest from other NATO countries.

Japan has a strong interest in scramjet and combined-cycle engines. An accelerating technical effort is evident. Programs include the development of a methane-fueled ramjet capable of stable flight to Mach 5.0 and of a small combined-cycle ramjet/turbojet engine. Japan also has initiated a major effort to enhance its aerospace materials and propulsion capabilities by the formation of the Material Research Center and Institute to study ultra-heat-resistant materials applicable for use up to 2000°C. If successful, this research could make major advances in the field of hypersonic air-breathing propulsion.

Overall, considerable capability is being developed by our free world competitors which is not matched by corresponding revolutionary work in the United States.

2. Exchange Agreements

Formal exchange in air-breathing propulsion was found to be limited and primarily focused on advanced ramjet propulsion for weapons. This reflects, in large part, the nature of the international commercial infrastructure. This infrastructure is characterized by intense competition among firms that have already established international marketing and manufacturing relationships.

As a result, primary interchange in this area occurs under Air Force data exchange agreements and Memoranda of Understanding (MOUs) with various NATO allies. The areas of exchange encompass technologies related to materials and test techniques. Of specific note are the ties established with the French in ramjet-related and carbon material technologies. The French are considered world leaders in these areas.

In addition, the Navy has exchange programs with NATO allies in certain aspects of engine materials and in marine gas turbine propulsion. This area will benefit directly from many of the exchanges identified in the section on computational fluid dynamics.

15. PULSED POWER

15. PULSED POWER

A. DESCRIPTION OF TECHNOLOGY

Revolutionary changes in battlefield scenarios are possible because of major improvements in pulsed power technology that allow the development of high-power weapons and sensors. Advances are required to develop high-power weapon systems and sensors including directed energy weapons (DEW), kinetic energy weapons (KEW), improved target identification and surveillance systems, and rapid fire earth-to-orbit (ETO) launchers. DEWs (lasers, microwaves, and particle beams) provide speed-of-light operations with high firing rates at long ranges, capable of destroying or disabling missiles and other targets. KEWs utilize hypervelocity projectiles for long-range engagements, rapid fire rates, and deep magazines for anti-missile and anti-armor defense. In addition to directly powering battlefield systems, pulsed power technology is vital to assessing and simulating the vulnerability and lethality of present and future systems to nuclear, DEW, and KEW systems. Essential to these efforts are reductions in the size and weight of systems and improvements in reliability and maintainability.

Critical component technologies for pulsed power systems are repetition rate, energy storage, pulse forming (conditioning) networks (PFN), and coupling pulse to load (e.g., laser, high-power microwave tube). The prime power (generator, battery, etc.) system delivers energy to the storage subsystem. The pulse forming network transforms the energy to match the load requirements. High-pulse repetition frequency (PRF) energy storage subsystems require light-weight, high-efficiency, and compact energy storage using inductors and capacitors. Compact energy storage systems must have high energy densities (kJ/kg) to lessen military system weight. The PFN shapes the high-power pulse with capacitors, inductors, switches, and nonlinear elements and couples it to the load. Most systems require a high-power output switch between the PFN and the load. High peak power systems utilizing non-linear pulse compression and ultra-wide bandwidth RF are also critical.

Pulsed power energy storage systems often consist of large high-voltage, highcurrent capacitor banks that have compact modular design. High energy density capacitors with low inductance and fast current rise times are necessary for light weight and high repetition (up to 10 kHz) rates. Improvements in energy density between 1985 and 1989 reduced the mass of a 50 kJ capacitor by a factor of 10, from 150 kg to 15 kg. The increased energy density reduces the cost per joule, which makes advanced electromagnetic launchers feasible for launching payloads into earth orbit.

For single-shot applications, explosively powered systems based on magnetic flux compression can reduce size and weight by a factor of 10 to 100 compared to capacitor systems. For large platforms, rotating machinery storage can be competitive with large capacitor banks for long discharge times.

Two basic types of PFNs are important for pulsed power: inductive and capacitive energy storage. In the inductive energy storage system, the energy stored in the capacitors from the prime source is stored in an inductor/capacitor (PLC) network. Switches then transfer energy to the load. In the capacitive energy storage system, however, the network shapes the output pulse. Strategic defense applications using electromagnetic launchers require a tenfold improvement in inductive energy storage. High-pulsed power applications need improvements in gaseous and solid state switch technologies. Applications of inductive energy storage (IES) for nuclear weapons effects simulation require improvements in switch conduction time, opening time, and opened impedance.

Significant improvements are required in opening and closing switch technology for transferring the power from the PFN to the various weapon system loads. The switch must be designed to meet specific PRFs, sustained conduction time intervals, and rise-time and fall-time characteristics. The most important gaseous switches are spark gaps, ignitrons, and thyratrons. Gaseous switches require increased reliability, higher voltages, and greater current capacities to meet today's needs. Solid-state photoconductive/semiconductor switches (PCSS) offer new alternatives: high power, short pulses, light weight, and direct sources of precisely timed pulsed power. In conjunction with repetitive, high-density capacitors, PCSSs provide low-cost, light-weight microwave sources for ultra-wideband radars, high-power microwave weapons and countermeasures, lasers, and particle beams. High reliability, fast, high voltage, repetitive opening swiches are required to develop the advantages of inductive energy storage.

Technology Sets in Pulsed Power

- Energy storage
- Opening and closing switches
- Conditions circuits
- Prime power sources
- High power microwave

B. PAYOFF

1. Impact on Future Weapon Systems

Pulsed power is a critical element for the development of the following potential weapon systems: high-power microwaves, electrothermal and electromagnetic guns, neutral particle beams, space-based free electron lasers, ground-based lasers, and charged particle beams. Pulsed power is also essential for the development of other systems such as laser radars, ultra-wideband radars, electromagnetic armor, and nuclear weapon effects simulators. The table below shows the critical pulsed power parameters and the potential weapons likely to use that technology. A description of the most important weapon applications follows.

a. High-Power Microwaves

High power microwaves (HPM) provide a speed-of-light weapon or countermeasure that may cause mission abort for some kinds of systems or may prematurely set off explosive components in other kinds of systems. Narrow bandwidth systems are being developed for beamed weapon applications, and ultra-wide bandwidth systems are being developed for countermeasures. These weapons or countermeasures may temporarily confuse, blind, or upset important sensors; damage critical electronics so that they cannot function until physically replaced; and disable, disrupt, or upset electronic control circuits. Successful development requires advances in radio frequency (RF) power sources, pulsed-power conditioning, frequency or time coherence control, and antenna technology. Development is also necessary to improve system ruggedness, reliability, and repetition rate.

Critical Parameters in Pulsed Power

Pulse Power Aplications / Pulse Power Components	Electromagnetic launcher	Electrothermal launcher	Earth-to-orbit launcher	Ultra-wideband radar	Underwater acoustic sources	Nuclear weapon effects simulators	Laser radar	Neutral particle beams	Charged particle beams	Ground-based free electron laser	Space-based free electron laser	High-power microwave	Electromagnetic armor	Mine clearing
Capacitive energy storage	X	X	X		X	X			X			X	X	X
Rotating Machine	X	X	X		X	X							X	X
Voltage converters storage								X	X		X			
Pulse-forming networks		X		X	X	X	X		X			X	X	
Switches	X		X	X	X	X	X		X			X		
?ir sources				X				X		X	X	X		X
Prime power			X			X		X	X		X	X		X

b. Electrothermal Guns

The Services are exploring the development of electrothermal guns. The Army can use electrothermal guns as an extended range (3 to 5 km) anti-armor weapon that will be lethal against the next generation of tanks to be fielded by potential adversaries. The Navy has an urgent need for a weapon that can be mounted in surface ships to intercept and destroy present and future missile systems at distances greater than 15 km. The Air Force can use electrothermal guns for close-air support aircraft, such as the A-10, to destroy armor on the ground at ranges of up to 5 km. The development of compact, mobile, conditioned pulsed-power is one of the critical links to develop these weapons.

c. Electromagnetic Launchers

Electromagnetic launchers can be used for strategic applications as a terminal defense weapon to destroy oncoming missiles and in space platforms to destroy reentry vehicles. To develop these potential weapons, a significant advance in pulsed power is required. If a rotating machine or inductive energy storage system is used, multi-Hertz opening switches with PRFs of a few Hertz and conduction times of hundreds of microseconds are needed to use hundred Megajoule energy storage inductors. Using a capacitive energy storage system with a 0.5 to 5 MA closing switch (and a PRF of a few Hertz) requires a 2 to 5 millisecond conduction time. Electromagnetic launchers need a fivefold increase in capacitor energy storage density to launch large size masses into orbit. Coilguns would directly benefit from the development of lower cost energy capacitors and an improved capacitor service life. Complex rotating flux compressors (compulsators) in conjunction with heteropolar electromagnetic launchers with variable structures offer great promise for the future.

d. Neutral Particle Beam

Neutral particle beam (NPB) systems are currently under development to discriminate decoys from reentry vehicles for strategic defense but are also effective for anti-satellite (ASAT) missions. A light ion beam is accelerated and neutralized before leaving the platform. At sufficiently high beam energies, the beam deeply penetrates into the target, producing markedly different effects in decoys vs. actual weapons, and, at higher energies, damaging the electronics, detonating the high explosive within the reentry vehicles, and producing structural damage. Continuous wave ultra-high frequency (UHF) radio frequency sources are the most crucial pulsed power technology required to make NPB systems practical.

e. Space-Based and Ground-Based Free Electron Lasers

Free electron laser (FEL) systems are under development by the Strategic Defense Initiative with potential applications for ground and space defense. For strategic defense applications, high-energy laser beams would kill both booster and post-boost vehicle structures. ASAT weapons and ship-based anti-missile defense (ASMD) may use FELs. A key pulsed-power technology is the RF source required to drive the free electron beam.

f. Charged Particle Beam

Charged particle beam (CPB) systems are being considered for ship-based ASMD weapons and pop-up interactive discrimination of targets in strategic defense applications. An electron beam is accelerated by a repetitively pulsed induction type accelerator. Switching is the key pulsed-power technology for this application. Precision photoconductive semiconductor switching is ideally suited for this application because of the rapid switching of high voltages at high peak powers. In addition, light-weight DC/DC inverters will be needed to transform the low DC voltage to the high DC voltage required by the primary energy storage capacitor and PFNs. This will require very high energy systems.

g. Ultra-Wideband Radars

Ultra-wideband (UWB) radars have three interesting features: low frequency, high-clutter detection in foliage; low-cost target imaging; and real-time target identification. They however suffer from lack of average power to long range performance. UWB radars require precise temporal control of a few tens of picoseconds to achieve coherent transmission and reception. Precision controlled switching with very low jitter (a few picoseconds) and extremely fast modulation rates are required for the development of these new types of radar waveforms. UWB radars (discussed in section 7) have very high range resolutions, and the ultra-wide bandwidths simultaneously measure the low frequency (Rayleigh), the resonant and the high frequency signatures of a radar target.

2. Potential Benefits to industrial base

Significant spin-off of pulsed power and power conditioning technology to the commercial industrial base is already occurring. New commercial applications are occurring, the majority in the electric utilities, electric drive and control industry, and the medical industry. Several examples of specific spin-off applications are described in the following paragraphs.

The DoD Mile Run energy storage capacitor development program (jointly sponsored by the Strategic Defense Initiative Office (SDIO) and the Defense Nuclear Agency) has achieved dramatic increases in energy density within the last few years. High energy density capacitor availability is making the pulsed metal forming industry more cost competitive. At least one automobile corporation is using this approach to affix end caps to driveshafts. The electric utility industry is interested in using high–energy density capacitors for power factor correction because they are installed on a utility line by a single technician. Significant cost reductions are among the development goals for pulsed–power accelerators, which also will help to reduce costs of commercial accelerators for medical applications. Molecular engineering techniques used to develop high energy storage capacitors have been useful in the development of heart defibrillators.

Many high–power switch developments have been pursued by DoD, and several of these devices are being used in commercial applications. Hydrogen thyratron switches originally developed for the SDI ground–based laser are now used by a manufacturer of ultrasonic kidney stone break–up machines. Less mature, but more significant, is a new type of solid–state switch, the MOS Controlled Thyristor (MCT). The MCT is a highpower, efficient electric motor controller switch. The MCT makes possible automobile industry plans for the demonstration of front–wheel drive vehicles with electric motor drives for enhanced traction. The electric utility industry will use MCTs for future fault management switchgear and power processing un... for DC–DC transmission lines.

Long–term development of high–power switches by DoD will affect the competitive position of the United States by making compact, efficient, and agile power systems available. UWB pulsed–power technology will provide more efficient, agile, and versatile pulsed–power sources for narrow and wide bandwidth RF applications. Several companies are developing precision switching technologies to synthesize narrow and ultrawideband RF pulses for radars and countermeasures.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

The objective of Pulsed Power technology is to provide extremely high peak power, low duty cycle pulsed sources to develop a new class of technologies in propulsion, weapons, and radars

In order to realize the technology opportunities offered by Pulsed Power, reductions in size and mass of components is required while requiring improvements in energy density, electrical efficiency, reliability, and control of pulsed waveforms. Progress in these areas will determine the practicality of high energy systems and the potential applications: high power microwave, electrothermal guns, electromagnetic launchers, ultra–wideband radar, underwater acoustic sources, nuclear weapons effects simulators, laser radar, neutral and charged particle beam, and ground– and space–based free electron lasers. The development plan will examine the critical elements of this technology set.

a. Energy Storage

(1) Objective

Efficiently store at high density sufficient energy for mission accomplishment. Two types of energy storage are envisioned: inductive and capacitive. Inductive systems require perfection of opening switches while capacitive systems require perfection of closing switches. Milestones for inductive (I) and capacitive (C) techniques follow.

(2) **Development Milestones**

- In the near term (FY 1992) demonstrate energy densities to 10 kJ/kg (I) and 3 kJ/kg (C) with 10^8 shot lifetime. Laboratory experiments continue for directed energy and armor/anti-armor applications.
- In the mid term (FY 1994–FY 1995) improve energy densities about threefold to 30 kJ/kg (I) and 10 kJ/kg (C). These improvements make armor/anti-armor guns practical and begin to enable mine-clearing operations.
- In the far term (FY 1997) further improve energy densities to 1 MJ/kg (I) and 30 kJ/kg (C), thus paving the way for high performance directed energy weapons. This would meet the pulsed power requirements for hypervelocity electro-magnetic guns, allowing Sabot/shell velocities of >20 km/sec.

b. **Power Switching**

(1) **Objective**

Develop both closing and opening switches and high repetition rate operation utilizing plasma, solid state, and magnetic elements.

Pulse power switches are required to transfer the energy to the load. The critical issues are the development of opening switches and high repetition rate closing switches. Opening switches are required to take advantage of inductive storage technology. High repetitionrated switches are required in many specific applications. Additionally, sensor applications use precision switching of tens of picoseconds, and some weapons require very high peak power at the gigawatt level.

(2) **Development Milestones**

The milestones for switch development are characterized in two ways for both opening and closing switches: current density and rise time of current for the highest peak powers. The milestones are:

- For the mid term (FY 1993–FY 1994) improve current density from 400 to 1000 amp/cm3 and in the far term (FY 1997) achieve 10^8 shot lifetime. For E&M guns and artillery this is a key improvement.
- Achievement of 10^{14} A/s risetime in the mid term (FY 1993) for ultra-wideband radars is important. Single pulse operation (low repetition rates) should be achieved first.
- In the far term single pulse rise times of 10^{14} A/s are extended to high repetition rate operation. Repetition rates should be improved from tens of Hz to tens of KHz. Some burst mode operation of tens of MHz are required.
- High power solid state switching; 10 kV, 100 kA units to replace orientation-sensitive ignatrons for new power systems based on high energy density capacitors (FY 1995).

c. **Conditioning Circuits**

(1) **Objective**

Efficiently transform (with minimum energy loss) and deliver the energy in a usable form for specific applications. Rise time, repetition rate, pulse length, etc., are all dependent upon the critical application.

Voltage converters are a major element of power conditioning circuits. They are used in power supplies for applications of various direct energy weapon systems such as neutral particle beams, charged particle beams, and space-based free electron lasers. Since this system is to be used for space applications where weight is a key factor, the challenge in this technology is to increase the power per unit mass.

(2) **Development Milestones**

The milestones emphasize the performance of conditioning circuits for various applications. There are various requirements from very high energies for rail guns to very fast, short pulses for radars. The average milestones are:

- In the mid term (FY 1993–FY 1994) improve by a factor of two from 2,500 kg/MW to 1,200 kg/MW the conditioning circuits for directed energy weapon applications.
- In the far term (FY 1997) further improve conditioning for the most demanding directed energy weapon applications to 700 kg/MW.

d. **Power Sources**

(1) **Objective**

Provide efficient and compact energy sources (batteries, fuel cells, and power generators) for enabling applications.

Fuel cells need to be developed for space-based power applications such as laser radar or entry-level directed energy weapons. In the near term the most important development is the space-proven alkaline technology. Current development programs being demonstrated in the laboratory are rapidly increasing the power density. Extension of these programs to achieve about 700 g/Kw in the next few years appears to be quite feasible. Present fuel cells are highly modular and can be configured as a central power plant or distributed as local sources along the length of an accelerator or other load. Present voltage output is limited to a few hundred volts DC, requiring step-up to 10's of kV to drive RF tubes. In the longer term, proton exchange membrane (pem) fuel cells offer similar performance and improved reliability.

Batteries are often used as the prime power source in applications where the voltage level does not exceed a few hundred volts DC. Since batteries are heavy, one of the present challenges in developing this technology is to increase the energy per unit mass. The present goal is to develop batteries with about 16 watt-hour/kg in the next few years and thereafter develop super-batteries with a 100 watt-hour/kg. There is no single leading organization in the DoD and/or DoE in battery research. Batteries are of primary importance to all the organizations.

The development of turbo alternators as a source of prime power is essential for ultra-wideband radars, neutral particle beams, space-based free electron lasers, electromagnetic and electrothermal launchers, high power microwaves, or any system that requires multi-megawatt power levels. For efficient deployment of space-based systems or mobile launchers for the Army, the mass per unit power delivered by the alternator must be reduced. With the present emphasis by the Military Services and the Strategic Defense Initiative on developing this technology, alternators with about 10 kW/kg should be achieved in the next five years.

(2) **Development Milestones**

In general, two basic types of sources are of interest: very high efficiency; and high peak power/low duty cycle types. The performance milestones are based upon average power per unit mass for efficient and exotic applications.

- In the mid term (FY 1993) efficiencies are approaching 2.5 kW/kg. These values are of interest for space applications stressing high peak power/low duty cycle operations.
- In the far term (after FY 1997) as efficiencies of 20 kW/kg are achieved, then electric vehicles for transportation become feasible.
- Solid state voltage conditioning: voltage invertors (AC to DC) at 20 kW/kg and voltage converters (DC to DC) at 10 kW/kg suitable for a megawatt system (FY 1997).

e. **High Power Microwave**

(1) **Objective**

Provide very high peak power relativistic, solid state, and wideband sources for various applications of HPM weapons or jamming equipment.

(2) **Development Milestones**

Basic component sources are required for varying frequencies, pulse widths, and duty cycles with high energy per pulse. Beyond the energy source generation is the achievement of efficient radiated energy from new types of mode converters and antennas. The energy per pulse milestones are:

- In the very near term (FY 1991) 50 J/pulse has been achieved in microsecond pulses at frequencies of a few Gigahertz.
- In the mid-term (FY 1994/FY 1995) the goal of 500 J/pulse will enable the first weapons and jammers to be developed in the laboratory.
- In the far term (FY 1996) the goal of 10,000 J/pulse will begin to enable HPM weapons and jammers for specific military missions provided sufficient repetition rates can be achieved.
- 500 kW CW RF sources at 75 percent DC-to-RF conversion efficiency, 500 MHz to 1000 MHz, 4 kW/kg for advanced lightweight RF accelerators (FY 1996).

2. **Technology Objectives**

3. **Resources**

A summary of total S&T funding is shown in the table below.

Technology Objectives — Pulsed Power

Technical Area	By 1996	By 2001	By 2006
Energy Storage Inductive Capacitive Explosive generators Rotating machines	•10^4 J/kg at 1 Hz, 10^4 shots •25 J/kg at 100 Hz and 10^8 shots •10^5 J/kg (explosive generator •80 J/kg pulse (rotating mach)	•$2x10^4$ J/kg at 1 Hz and 10^8 shots •100 J/kg at 100 Hz and 10^8 shots •$3x10^5$ J/kg (explosive generator) •80 J/kg pulse (rotating mach)	•$3x10^4$ J/kg at 100 Hz and 10^8 shots •1 kJ/kg at 100 Hz and 10^8 shots
Power Switching Open Closed Rep rated Gaseous Solid State	•100 kV at 10 kHz •0.3 nsec risetime at 10 Hz •10^{14} A/sec single shot •1 μs conduction; 10 ns open	•10^{14} A/sec at 10 Hz •3 μs conduction; 2 ns open	•10x improvement in average power capability •10 μs conduction; 2 ns open
Conditioning Circuits Peak power Rep rate Alternators/inverters Voltage converters	•100/500 kg/MW alternators/inverters •1000 kg/MW voltage converters	•20/300 kg/MW alternators/inverters •300 Kg/MW voltage converters	•100 kg/MW voltage converters
Power Sources Batteries Fuel cells Power generators Compact accelerators	•20 MeV at 10 kA single shot (compact acc.) •700 g/kW fuel cells •16 watt-hr/kg battery	•500 MeV at 10kA and 10 Hz (compact acc.) •260 g/kW fuel cells •100 watt-hr/kg battery	
High Power Microwave Relativistic Solid State Wideband	•1 kJ/pulse per 10 pulse burst at 1 kHz rate (HPM) •10 GW (relativistic)	•10 kJ/pulse per 10 pulse burst at 1 kHz rate (HPM) •50 GW (relativistic)	•100 kJ/pulse (HPM) •100 GW (relativistic)

Funding — Pulsed Power ($M)

FY87–91	FY92	FY93	FY94	FY95	FY96	FY97
541	76	76	81	80	80	82

4. **Utilizing the Technology**

The Joint Directors of Laboratories (JDL) recognized the importance of pulsed-power components and subsystems to critical DoD weapons, radars, and electronic warfare (EW) systems was recognized by by establishing a tri-Service pulsed-power team to assess US resources to high-energy, high-power programs for future military system requirements. A combined 6.1 and 6.2 level program in pulsed power technology development that also provides the technology-based teams among university, national laboratory, and private industry participants, would enable specific applications to be defined and funded by mission agencies within DoD and DoE. Some of these missions can be enabled with the technology at the end of the 6.2 phase. Some, however, may require extension into the 6.3a phase to show revolutionary capability with these new technologies.

The development of advanced high-energy-density (HED) storage will affect both mobile and fixed applications. Cost studies indicate that a 50 to 250 kilogram satellite could be launched by an electromagnetic system into a low earth orbit for only 3 to 10 percent of the present launch costs. Launch on demand to low earth orbit for reconstituting satellite constellations or for almost real-time reconnaissance has significant military utility.

Both the Army and the Navy have identified missions requiring electromagnetic (EM) launchers or electrothermal (ET) guns using order of magnitude improvements in energy density. An Army tank-mounted EM gun to penetrate advanced armor is needed as well as an extended range artillery piece for Army or Navy use.

Some new applications become practical with the development of advanced capacitor technology. Electrically driven surface-discharge acoustic sources would become practical for active submarine detection over large areas of the ocean. The payoff in this approach (over more conventional means) is the precise control of the acoustic waveshape to achieve optimal signal-to-noise ratio for detection at a given range. Future semiconventional acoustic sources will require compact mobile primary power sources with peak electrical powers at least 10 to 100 times the present systems.

High-voltage thyratron switches are required for HPM weapons, countermeasure systems, and ultra-wide bandwidth radars. Thyratron switch output can be sharpened through nonlinear shock techniques to increase the bandwidth for radars and countermeasures. This technology has already demonstrated 4mw peak power at a continuous repetition rate of 20 khz.

Development of the high-power MCT enables efficient electric drive for Army tanks, integrated ship electric-drives, and long endurance aircraft drives. Laser radars and other sensors significantly benefit from MCT devices.

The development of advanced solid-state switches will be required for many types of RF radars and countermeasures. UWB radars may require optically triggered photo-conductive switches to be effective. Charged particle beam systems for ship defense and for interactive discrimination of re-entry vehicles from decoys also require the new switch technology.

Explosively driven systems enable highly portable, single-shot devices applicable to some military situations. Explosive systems combine the power source, energy storage, and power conditioning functions into a single component for several classes of applications. System power and energy densities currently exceed those of capacitors and rotating machines. Improvements of a factor of 3-10 can reasonably be expected with development before physical limitations are encountered.

For non-defense applications, an entire class of high-power accelerators with solidstate amplifiers with fast starting times exists. DoD and DoE development of RF and pulsed power will have direct applications for: fusion energy production, nuclear particle physics; radioisotope production of medical isotopes; radiation therapy; materials, metals and plastics: ion implantation in semiconductors; and neutron analyses (neutron radiography of luggage). High-energy electron accelerators have additional applications such as radiation therapy, industrial radiography, sterilization of medical tools, food preservation, free-electron lasers and synchrotron light sources, and waste treatment. A potential application for future NASA missions might include high-power transmission of energy from ground to space or between space systems, and the low cost launch of fuel and materials into low earth orbit and moon-to-earth transportation.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

Domestic manufacturing firms have almost no incentive to become involved in the low volume pulsed-power market. Pulsed high-power for military applications continues to be needed for only applied and basic research efforts. For many years, pulsed high-power systems were only required by large one-of-a-kind facilities for weapons effects testing and fusion research. The manufacturing situation led to many small, research-oriented companies filling the requirements for limited quantities of pulsed-power components and hardware. Large companies supplied components to the military only as a sideline to their main commercial business. Solid-state switches and pulsed-power semiconductor devices formerly made in the United States now must be purchased overseas. The advent of modern high-energy beam weapons concepts such as high-power lasers, particle beam weapons, electromagnetic guns, and high-power microwaves, increased interest in pulsed power systems. Work on these devices is research-oriented, and major reductions in the size and weight of the associated power systems are required to field a portable system. In the current environment, the organizations supporting the military's pulse power programs are research or university oriented.

The manufacture of high-energy density capacitors depends on computer-controlled precision machines, purchased from a foreign source. As larger devices are required, larger machines with precise control will be needed.

The ultimate power handling performance of solid-state switches depends on the impurity level in the semiconductor substrate. The Japanese have the world's leading ability to produce large GaAs wafers.

2. Projected Industrial Capabilities

The technology required to build pulsed-power systems that meet the size and weight requirements necessary for high-volume production is not available. Sufficient system definition and program direction may be available by 1995. The commercial power industry will provide little support because the rise times and pulse rates required for their systems are generally much less than those specified for military systems. Potential manufacturing technologies of interest include solid-state and gas discharge switches of the opening and closing type, inductive storage devices, capacitors, batteries, and homopolar generators and compensated alternators. Commercial activities are underway to efficiently synthesize RF signals (both narrow and wideband) from DC to RF. No producibility or reliability have yet been demonstrated for either radars or communications, but some research is being carried on by private industry.

E. RELATED R&D IN THE UNITED STATES

The National Institute for Standards and Technology is developing technology to measure, with high degrees of accuracy and reliability, pulses having characteristic times between one msec and one nsec, voltages greater than 10 kV, and currents greater than 10 kamps. These technologies are mainly for use in research, development, and procurement by the electric power industry as well as fusion research, space power sources, and nuclear weapon simulations. Another program related to HPM is developing the theory and measurement techniques to characterize the out-of-band performance of antennas to determine their susceptibility to high power RF.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

Pulsed-power conversion technology encompasses techniques for conversion, storage, pulse-forming, and transmission of electrical energy to power a variety of weapons (lasers, KEW, HPM, or particle beams) or high-powered radars and electronic countermeasures. Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Reduction in size of power systems and components by an order of magnitude
- Development of photo-conductive, and solid-state switchs
- Development of HPM sources.

The table on the following page provides a summary comparison of the United States and other nations in selected key areas of pulsed power. The United States is the undisputed free-world leader in the development of compact, light-weight power systems for a variety of applications. Recent breakthroughs in U.S. capacitor fabrication (increasing energy densities by an order of magnitude) have established a significant U.S. lead in this key niche technology. However, the Soviet Union has an extensive program in pulsed power (e.g., using pulsed magnetohydrodynamics) and may possess a lead in other areas.

Opportunities for cooperative research in pulsed power will generally be limited to NATO and Japan in niche technologies relating to switching or specific applications, although cooperation with the USSR in explosive pulse power is now thought to be possible. In addition, there is potential for cooperation with NATO countries and Japan in a range of technologies that might be used as primary power for pulsed systems. Japan could make significant contributions in materials for photo-conductive switching.

The Soviet Union has developed high average power repetitive pulsed power technology that is more portable than the US equivalent. The Soviets are the current leaders in this field; in fact, they may well be in the lead in some key technology areas, particularly gaseous switching and inductive energy storage. In general, the Soviet Union has developed explosive pulsed power technology far more extensively than has the US. As a result, the Soviets have a much broader experience base then does the U.S. and their capability likely leads that of the U.S. by some amount.

The United States is assessed to have a significant lead in the development of high efficiency space-qualified solar arrays, a candidate for a primary power source and a potential key element of an overall pulsed power system. The most advanced cells to date use GaAs technology, in which both our NATO partners and Japan are active.

High energy capacity/high rate batteries have a potential role in SDI test beds, and potentially as components of operational systems. France has an active and broad-based program in both primary and secondary batteries, and could potentially contribute to cooperative research in this area.

Summary Comparison — Pulsed Power

Selected Elements	USSR	NATO Allies	Japan	Others
Reduce size of power systems and components by order of magnitude	☐☐ [a,b]	☐☐	☐☐	
Development of photo-conductive solid-state switch	☐☐	☐☐	☐☐	
Develop HPM sources	☐☐☐☐ +	☐☐☐ +	☐☐	
Overall[b]	☐☐☐☐ [a,b] ○	☐☐	☐☐☐ [b] ○	☐☐ [c] Various Countries

[a] The Soviets have developed a number of alternative technology approaches; overall, they are on a par with the United States.

[b] Strong in primary power sources that may prove adaptable to pulsed power systems.

[c] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

- ☐☐☐☐ broad technical achievement; allies capable of major contributions
- ☐☐☐ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
- ☐☐ generally lagging; allies may be capable of contributing in selected areas
- ☐ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

- \+ Foreign capability increasing at a faster rate than the United States
- ○ Foreign capability increasing at a similar rate to the United States
- — Foreign capability increasing at a slower rate than the United States

US government funding for pulsed-power R&D is divided among the national laboratories, private industry, and universities. The same is generally true internationally, except in Japan. There, in addition to government-funded R&D in pulsed-power, Japanese industry is funding several university programs for developing repetitive electron and ion beams for materials processing. Japanese GaAs technology might also have potential future uses in active array pulsed microwave power generation.

In Germany, Soviet Union, France, the UK, and the PRC, the vast majority of pulsed-power research and development is funded by the government, using national laboratory and university components. Funding for military applications is generally level but with increasing funding for commercial applications.

In the pulsed-power-related fields, effective two-way exchanges exist. Although joint developments are rare, initiatives from the Japanese, the Soviets, the Israelis, the British, and the Germans are planned or under way on a small scale.

Basic research results are exchanged in international forums. X-ray sources from the Soviet Union, basic experiments on ion beam treated surfaces from Japan and the Soviet Union, new materials from Japan, diagnostic and basic research on fundamental physics from Germany, France, and the Soviet Union, and new product designs and international meetings involving the Soviet Union, Japan, Germany, and other countries characterize multi-national exchanges. Exchanges are generally limited to basic research results and bulk materials needed for components.

2. Exchange Agreements

There is significant international exchange in basic research on inertially confined fusion and high energy physics. The Air Force has an exchange program in laser and RF systems with NATO; the Army has a similar program in high-power microwaves. The SDI program has MOUs with several countries, under which interchange of pulsed-power technology is possible.

16. HYPERVELOCITY PROJECTILES AND PROPULSION

16. HYPERVELOCITY PROJECTILES AND PROPULSION

A. DESCRIPTION OF TECHNOLOGY

Hypervelocity projectile technology involves the capability to propel projectiles to greater-than-conventional velocities (over 2.0 km/sec), as well as understanding the behavior of projectiles and targets at such velocities. Propulsion systems that are being investigated include electromagnetic guns (railguns and coilguns), electrothermal guns, traveling-charge guns with liquid or solid high-energy propellants, hypervelocity rockets, and explosively driven shock tubes. New designs of armor-piercing rod-shaped charges, explosively formed penetrators, and long-rod kinetic-energy projectiles are also being developed.

In designing hypervelocity projectiles external ballistics, such as the aerothermodynamic environment, control mechanisms, drag reduction, and impact and penetration of the targets, must be considered, as well as the interior ballistics associated with the actual launch mechanics of such projectiles. Critical technology challenges in hypervelocity projectiles are listed in the table below.

The highest priority thrusts for both tactical and strategic applications include: development of launchers and associated propulsion systems; high-g miniature guided projectiles; characterization of projectile environment in the launcher; projectile flight and stability in the atmosphere; pulsed high-power/compact-power supplies; high-energy density capacitor technology; homopolar generators; high-power density alternator technology; composite materials development; mega-ampere opening switches; multishot capabilities; electromagnetic launcher (EML) system integration; and superconductivity.

Technology Sets in Hypervelocity Projectiles and Propulsion

- Projectile design
- Projectile propulsion
- Projectile-target interaction

B. PAYOFF

At the tactical level, it is imperative that US antiarmor weapon technology keep pace with the new generation of armor fielded by potential adversaries. At this time, developments such as reactive armor and complex, multi-layer armors have made it doubtful that the current antiarmor weapon inventory will be able to defeat all threats.

Hypervelocity projectiles provide more penetrating and destructive capability. Their greater kinetic energy for a given mass and their higher velocities enhance effectiveness against all armors.

The effective range of conventional unguided anti-aircraft projectiles is limited to several kilometers, since the targets can maneuver out of the line of fire during the projectile's time-of-flight. As compared to a standard gun-launched projectile, a hypervelocity projectile's time-of-flight to the target is significantly decreased, thereby increasing the weapon's effective range.

On a strategic or theater level, a ground-based hypervelocity gun (HVG) element could intercept re-entry vehicles (RVs) in their endo-atmospheric phase of flight, or it could be used for launching an exo-atmospheric projectile for a mid-course intercept. It has the advantage of a high rate of fire at a low cost per projectile, and high velocity, which permits multiple engagements of incoming RVs, cruise-type missiles, or low flight trajectory sublaunched targets. However, HVG emplacement costs and efficiencies remain critical system issues.

At the strategic level, a space-based HVG platform may provide a viable interim to laser weapons for boost phase intercepts of advanced threat intercontinental ballistic missiles (ICBMs). A boost phase intercept provides the highest measure of deterrence since it can eliminate all RVs being carried by the booster with one shot. Since an adversary cannot predict which RVs are eliminated, he cannot predict targeting results. For inadvertent launches or short-range terrorist-type launches fewer space-based platforms would need to be activated, while slower velocity space-based interceptors (SBIs) may need to be activated.

By increasing the terminal effects per unit of projectile mass, some hypervelocity weapons designs also offer a potential reduction in the overall systems' mission weight.

Electromagnetic launchers can be used to launch small payloads, such as Brilliant Pebbles or small observation and communication satellites, from earth to low earth orbit.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Projectile Design

(1) Objectives

The objective of this technology is to develop a family of advanced projectiles effectively lethal against their intended targets and able to survive severe launch and flight environments. By virtue of the varied applications (e.g., EM guns, hypervelocity missiles, rocket-boosted projectiles, and traveling charge guns), projectile designs will satisfy tactical and strategic requirements for guided and unguided rounds in the velocity regime of 2 km/sec to 20 km/sec and muzzle energies up to 100 MJ.

(2) Development Milestones

- DoD is investigating a wide variety of kinetic energy impact configurations in the hypervelocity domain. Program objectives include major weapon level performance improvements for direct fire air defense, with a proven vehicle for a "smart" bullet launch package. The SLEKE program is the major element of the tactical hypervelocity gun program. The goals of SLEKE efforts fall in two areas: to minimize parasitic launch mass for an anti-armor long rod round and for a direct fire air defense round; and to maximize penetration in complex modern armor targets by employing advanced hypervelocity effects. The program leads to development and fabrication of SLEKE projectile packages for testing. It includes assessments on the mass vs. velocity tradeoffs in optimal exploitation of hypervelocity effects, as well as improved materials development and processing. Major milestones for this effort include 9 MJ projectile tests in FY 1991 and FY 1992, and 20 MJ tests beginning in FY 1995.

- Experimental and modeling efforts are underway to characterize fundamental physical processes in ETC propulsion. Plasma cartridges are being developed for creation and injection of the required hot ionized gas into the working fluid (propellant). These will lead to designs and testing of ETC armament demonstrators at the 15-18 MJ level by FY 1994/FY 1995.

- The SDIO Multi-Guided Projectile Technology Base/Leap is to demonstrate that it is possible to integrate a small, high performance, kinetic energy interceptor (missile launched) into a weight package less than 5 kilograms. This program is structured to provide technology demonstration by FY 1994 and will lead to the Leap-7 100 MJ tests in FY 1997.

- The X-Rod program is to verify the feasibility of an autonomous or command guided, high-speed kinetic energy penetrator against enemy tanks. This program will lead to prototype projectile designs which will be tested in FY 1994.

b. Projectile Propulsion

(1) Objectives

Develop electric gun and rocket technologies necessary to propel the required projectile masses to the velocities required for specific tactical and strategic weapon applications. Specific areas to be addressed include barrels, armatures, and plasma cartridges for electric guns and propellants for rockets.

(2) Development Milestones

- The EMG Barrel Technology/Development program addresses issues such as railgun: barrel strength, stiffness, lifetime, multi-shot, composites, cooling. All represent engineering problems that must be answered in order to derive weapons from this technology. Interim evaluations are scheduled in late FY 1994. Muzzle energies and barrel lifetimes have increased 100 fold in the last 5 to 7 years, while efficiencies have increased almost an order of magnitude. Multishot capabilities have improved from a few shots daily to 30-shot bursts at greater than 5 Hz. Efficiencies are already high enough for ground-based systems. Barrel lifetime and muzzle energies are within a fewfold of requirements for tactical systems.

- The EEF Design effort is to characterize fundamental physical processes at work in ETC propulsion. A test of the EEF design will occur in FY 1995.

- The Cartridge/Modeling effort is to design plasma cartridges for ETC guns. Such cartridges are devices for creating and injecting a hot ionized gas into the working fluid (propellant). DoD's program will fabricate and test a 155 mm ETC artillery system by FY 1995.

- The Plasma Mass Launcher effort will characterize fundamental physical processes at work in EM guns. The results of this work will be available in FY 1994 to support testing and evaluation efforts.

- Endoatmospheric HVG development will provide a laboratory EM gun, fire control, projectile, and power system designed to launch the D2 projectiles (120 mm). A test of the gun is planned for FY 1997. This SDIO-sponsored program will launch a 7 kg guided interceptor to 40 MJ (Megajoule) muzzle energy by 1992 and accelerate a 2 kg payload to 100 MJ by 1995. To supply power for the 40 MJ program, a low cost battery-based power supply has been selected to project 5 MA (million amps), providing 500 MJ of stored energy for powering 40 MJ projectiles at 1 Hz (Hertz) and 3 Hz rapid fire rates.

- The Exoatmospheric Thunderbolt effort includes development of a 56 mm EM gun, armature, and power system to achieve high velocity projectile launches. A test of a prototype system is planned for FY 1994.

- The X-Rod demonstration will include a "guide-to-hit" demonstration that will allow early resolution of critical design issues for an early AD/FSD decision on the concept. A test of the X-Rod is planned for FY 1995.

- Significant progress has been made in characterizing the Electromagnetic launcher (EML) projectile environment with the successful development of an in-bore instrumentation and diagnostic (IBID) package. IBID allows continuous sensing, digitization, and storage of in-bore data onboard a projectile and has been used to record projectile axial acceleration from the injector to soft-catch tank. Future plans will extend this measurement to lateral acceleration and further characterization of the in-bore environment.

:. Projectile-Target Interaction

(1) Objectives

DoD has several fundamental investigations whose objectives are to: define the physical basis of armor penetration; develop improved penetration mechanics; improve the modeling of high-rate deformation and failure; and study the thermochemical processes involved in both explosive detonation and detonation following the application of or exposure to intense heat (deflagration).

(2) **Development Milestones**

- Programs to develop basic understanding of projectiles-target interactions are designed to directly support the tests of various projectile and propulsion developments, many of which occur in the FY 1994/95 timeframe.

2. Technology Objectives

Technology Objectives — Hypervelocity Projectiles and Propulsion

Technical Area	By 1997	By 2002	By 2007
Projectile Design • Inbore "G" and EM – Sabots – Armatures – Projectiles – Guidance components – Maneuver components	**Demo Only** • Composite structure-based push projectile and armament • 50 kilo "G" components	**FSED** • Mid-riding, integrated sabot/armature • Mach 10 launch • 100 kilo "G" components	**Deployed Systems** • Guided anti-tank round Mach 6-10; long range MMW seeker • Segmented high density penetrator
• Hypervelocity Flight – Nose and heat shield – Airframe dynamics and materials – Stability, control, maneuver – Lateral propulsion	• Mach 6.0 guided projectile • 6-10 "G" lateral maneuver	• Mach 10 maneuver • 10-30 "G" lateral • <1.0 millisecond response	
• Guidance – Sensors, seekers – Processors – Algorithms; recognition – Acquisition and tracking	• 94 GHz seeker, processor, and algorithms	• Micro IMU • Miniature processor electronics • Demonstrated target recognition	• Demonstrated target recognition • Antiair/ATBM Mach 10, 15 km MMW seeker
Projectile Propulsion • Antiarmor System • Artillery System • Air Defense System • Strategic Defense System	• Complete 20 MJ EMORETC ATTD • Complete ETC ATTD	• Complete FSD of integrated propulsion/ projectile system	• Technology for advanced smart projectiles
Projectile Design • Interaction	• Mach 6.0 long rod, K.E. • Mach 6.0 extension of segmented penetrator • Area target HE warhead	• Microsecond fusing • ATBM intercept demo • Mach 10 high density segmented penetrator	

3. Resources

A summary of total S&T[15] funding for this critical technology is given in the following table.

Funding — Hypervelocity Projectiles and Propulsion ($M)

FY87–91	FY92	FY93	FY94	FY95	FY96	FY97
710	183	205	201	200	197	196

The Army and SDIO are the major DoD participants in this technology. The Navy is evaluating this technology for ship defense applications. DNA also has a program in this technology addressing ETC cartridges and related modeling. DoE's role in this technology is to support DoD development of advanced conventional munitions. The President's 1985 Blue Ribbon Task Group recommended broadening the traditional mission of the DoE nuclear weapon laboratories to encompass such priority national technical problems. The Joint DoD/DoE Advanced Conventional Munitions (ACM) program is a non-nuclear weapons technology program consisting of four related development programs. Each has as its basis a Memorandum of Understanding (MOU) between DoE and DoD providing the management and procedural framework for a cooperative program of research and development (R&D) intended to improve/reduce the cost of advanced conventional munitions. The four cooperative programs are: Department of Army (DA) Cooperative Program; DoE/DoD Office of Munitions Program; Low Intensity Conflict Program; and DoD/Defense Advanced Research Projects Agency (DARPA/Department of Army/Marine Corps) Armor/Antiarmor (A3) Program.

4. Using the Technology

In addition to weapons applications, railgun technology has led to new materials and manufacturing techniques involving hypervelocity impact deposition for a variety of applications, including manufacture of high-speed integrated semiconductor devices.

Electrothermal gun technology has generated substantial new weapons programs, not only in the U.S. but also in Germany and the Israeli Ministry of Defense. The coilgun technology base has allowed the Navy to begin new programs in electric launchers for aircraft, torpedoes, and sono-buoys. Railgun technology has expanded DoD's technology base with the successful integration of large-scale, low cost batteries; development of a multishot test bed for material and lifetime studies; and recent, in-bore data acquisition to validate the compatibility of guided interceptors with the railgun environment.

The components of the projectile technologies and the railgun technologies have been studied by SDI for intermediate strategic concepts for terminal defense.

The homopolar machine technology base provides the Navy with solutions for advanced motors and generators for the new all-electric ships. These machines have also found application in new sintering and welding techniques and powering confinement fusion experiments. DoD programs have also generated new classes of compact multigigawatt pulse

[15]Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is the right order of magnitude but is not to be construed as a precise budgetary quantity.

alternators, which are available to power the new generations of laser, microwave, and particle beam weapons.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Domestic Industrial Capabilities

At this point, electromagnetic launcher technology is several years from being incorporated in an operational weapon system. Major R&D efforts exist at the basic and applied research level; therefore, there is little domestic manufacturing capability at this time. Industrial base issues arise from specialized material requirements and small, light, inertial guidance and measurement units. The industrial base is considered sparse because of the lack of maturity and limited size.

Hypervelocity projectiles generate many different materials requirements that are unique to defense applications. Electromagnetic and electrothermal guns require new materials for rails, armatures, and electrodes that possess various combinations of lightweight resistance to electric arc erosion and resistance to electromagnetic forces. New materials are required for high length-to-diameter ratio projectiles, which must be stiff yet tough and for very light sabots. Material requirements for gun applications exceed those seen in non-defense applications. However, the potential production volumes are small compared to customary gun markets, and traditional materials producers have shown little interest in supporting development efforts. If new facilities and equipment are required to process the materials developed for these applications, DoD will be expected to bear the cost of the investment.

2. Projected Domestic Industrial Capabilities

The military services and DARPA are developing electromagnetic technology for use in strategic and tactical (primarily anti-armor) applications. Many domestic manufacturing and industrial base issues must be resolved before this technology can become viable, including

- Nose tip ablative materials that provide shape-stable nose tips capable of defeating reactive armor systems
- Development and fabrication of high-density, high-strength alloys for penetrator components
- Design and fabrication of high compressive strength, low-density support structure.

Guidance and Control (G&C) systems also place new requirements on the industrial base. Stringent accuracy, responsiveness, size, and weight requirements must be satisfied by IMUs of guidance systems and IMU components. The guidance industry is composed of vertically-integrated companies. Advancements in guidance technology have historically resulted from DoD investments in both R&D and manufacturing process development. Although other applications with less stringent requirements can also benefit from the results of R&D in this area, little private support for either R&D or establishment of production facilities is likely to come from the G&C industry because of the low production volumes.

E. RELATED R&D IN THE UNITED STATES

Research in electromagnetic gun systems is being carried out in several independent research laboratories and universities in the United States. However, funding support comes chiefly from the government for defense applications. DoE research has made significant contributions to related technologies.

Overall, the industrial base for electromagnetic launcher technology has been significantly reduced during the past few years due to the reduced funding levels of the government. Research is now primarily focused at the government laboratory level, a few small and large businesses, and several universities. At government laboratories and businesses, the focus has primarily been on projectile components and gun developments. The other groups conducting research have focused on basic research such as scaling, armature physics, diagnostic development, system configuration, trade studies, and experimentation.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

Hypervelocity projectile technology encompasses a wide range of techniques and materials required to obtain and maximize the effectiveness of projectiles at velocities greater than 2 km/sec. Ongoing research and development in the following areas indicate a potential capability to contribute to meeting the challenges and goals identified:

- Accurate characterization of projectile flight in atmosphere
- Effective use of advanced propulsion systems
- Application of advanced materials to kinetic energy penetrators
- Three-dimensional characterization of material reaction to warhead efforts.

The table on the following page provides a summary comparison of U.S. and other nations capabilities in selected aspects of this technology. The United States is on a par with the USSR in most of the related technologies.

The Soviets are known to have a considerable interest and probably a research program in the technology of kinetic energy rounds. Soviet work on the use of tungsten alloys for kinetic energy penetrators is well developed and they could have certain advantages over US technology in terms of armor penetration. The Soviets have a strong technological position in the development of high-power sources for electromagnetic or electrothermal guns and in some theoretical aspects of penetration mechanics.

The United States is the leader in all of the critical hypervelocity technologies, but in some areas other countries have comparable capabilities. The United States has the only launcher programs with the long-range goals of velocities about 10 km/sec for space-based application and high energy launches above 40 MJ in the near term. The United States, thus, is developing a considerable data base in understanding how to achieve such velocities.

DoD has joint hypervelocity gun programs with Israel, the UK, and the Netherlands. MOUs between these countries provide the basis for mutual access to research. However, since these allies are mainly interested in hypervelocity technology for tactical or theater weapons, any advances in space-based technology occur in the United States only.

Summary Comparison — Hypervelocity Projectiles and Propulsion

Selected Elements	USSR	NATO Allies	Japan	Others
Accurate characterization of projectile flight in atmosphere	□□□ –	□□□ –	□□	□□ Australia, Italy
Effective use of advanced propulsion systems	□□□ –	□□	□□	□□□ Israel
Application of advanced materials to kinetic penetrators	□□		□□	
3-D characterization of material reaction to warhead effects	□□□ [a] ○	□□	□□	
Overall[b]	□□□ –	□□	□□	

[a] Computation deficiencies may be offset by empirical experimentation.

[b] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□	broad technical achievement; allies capable of major contributions
□□□	moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
□□	generally lagging; allies may be capable of contributing in selected areas
□	lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

+	Foreign capability increasing at a faster rate than the United States
○	Foreign capability increasing at a similar rate to the United States
–	Foreign capability increasing at a slower rate than the United States

Discussions with Germany in the area of advanced chemical hypervelocity guns and Japan in the area of high-temperature switch and inductor technology have taken place.

Because of limited funding and the large capital investment cost required for performing high-energy, repetitive electromagnetic launcher research, the United States and its allies should operate on a mutual dependence basis as much as possible within the security guidelines. Relevant best data, innovative concepts, and manpower assistance should be shared whenever possible to ensure non-duplication of effort.

2. Exchange Agreements

There is a modest level of exchange activity in this area. The NATO Defense Research Group (DRG) program in physics and electronics may provide a mechanism for exchanges of fundamental scientific information in underlying technologies of materials and the physics of weapon target interaction. DARPA has exchanges with certain NATO countries in the area of anti-armor/armor technologies and has an MOU with the UK for electromagnetic gun and hypervelocity projectiles. SDIO has exchanges with certain NATO countries in the area of railguns and components.

The Technology Cooperation Program (TTCP) provides a vehicle for a range of applicable exchange activities in a number of closely related areas under conventional weapons technology and generic weapons system effectiveness. Again, the level of detail will be limited by classification.

There are only a few related Service exchange programs. These exchanges can, at the technology level, enhance our basic understanding of and ability to model target-weapon interaction and damage effects.

17. HIGH ENERGY DENSITY MATERIALS

17. HIGH ENERGY DENSITY MATERIALS

A. DESCRIPTION OF TECHNOLOGY

High energy density materials (HEDM) are compositions of high energy ingredients used as explosives, propellants, or pyrotechnics. They are used in almost all weapons systems, both strategic and tactical, and are fielded by all the Services. They provide the means of getting most ordnance items (whether a bullet, missile/rocket, or kinetic energy vehicle) to target, and once the ordnance item is near the target, they provide the means to kill the target (either by fragments or blast). Thus, HEDM are critical for:

- Strategic missile propulsion (strategic offense, deterrence, defense)
- Tactical missile propulsion (air defense, anti–ship strike, deep strike, interdiction, and close air support)
- Kinetic energy vehicle propulsion (space)
- Orbit transfer system propulsion (space)
- On–demand launch system propulsion
- Tactical missile warheads (air defense, anti–ship strike, deep strike, interdiction, and close air support)
- Torpedo warheads (sea combat)
- Bombs (close air support, sea combat, interdiction)
- Shaped charge warheads
- Mines (mine warfare)
- Countermeasures (sea combat, mine warheads)
- Components in nuclear devices
- Fuses.

Seemingly small improvements in HEDM performance can significantly affect weapon system performance. For example:

- A 10 percent increase in range for a sea–launched strategic missile results in several million additional square miles of ocean in which the submarine can conceal itself and still launch missiles to hit the target.
- Increased penetration capability of even a few centimeters can make the difference between penetrating tank armor, or the new hardened concretes, or not penetrating at all. Penetration most probably results in a kill, while non–penetration would result in a mission failure.
- As enemy airborne weapon ranges increase, air targets will have to be engaged at greater distances. These increased distances, coupled with the decrease in signature of the target will tax the ability of sensors to detect and guide the missile to the target. The potential

for increased miss distances necessitates higher performance warheads that use new HEDM. These increased lethality warheads are critically needed for the advanced air-to-air missile (AAAM) and related outer air battle missiles.

A recently synthesized ingredient, CL-20, shows promise that performance gains can be achieved in the near future. For example

- A solid propellant based on CL-20 provides a significant increase in range for air-breathing cruise missiles and allows the platform to launch missiles from a significantly deeper, safer depth.
- Energy increases of up to 20 percent are available from CL-20 explosives for coupling into shaped-charge jets for either increased penetration or increased hole size.
- Gun propellants based on CL-20 can increase the standoff range of tanks by approximately 1.2 kilometers and increase the projectile velocity by 50 centimeters/sec.

The pervasiveness and effect of HEDM on the performance of weapon systems warrants its selection as a critical technology.

Increased performance, while obviously desirable, is not the only major consideration in selecting HEDM as a critical technology. Other major considerations include hazards; signature reduction, primarily in missile propulsion; and availability, dependability, and reliability.

All three Services have programs to reduce hazards without degrading the operational capability of munitions and combat efficiency. As the energy density of the energetic materials has increased (more energy is incorporated into a given volume) the hazards of inadvertent initiation/ignition are also increased. This has serious implications including logistics/readiness (because of quantity-distance considerations, the Air Force and Army in Europe have difficult readiness/storage problems); vulnerability (the Navy has a large insensitive munitions (IM) program to decrease potential hazards of ordnance while maintaining operational capability); and performance/lethality (in many instances, performance and lethality have been sacrificed to decrease hazards). While each Service has its own IM programs, they also have joint efforts and are issuing IM requirements

All of the Services are involved in trying to reduce signatures produced by their propulsion systems in various areas. For example visible smoke confirms that a missile has been fired and evasive action is required, and it allows one to track back to the launch postion. Visible rocket smoke or muzzle flash also reveals soldiers' positions. In addition, visible smoke and incandescence of the plume from high-performance metallized propellants can be clearly seen by the human eye for many miles, giving a bearing on the missile location, and can be easily detected by satellite, showing that launch occurred and the bearing of the missile. As detectors and sensors have become more sensitive, we have been forced to increase the stealth of our aircraft. However, the stealth of the launch platform can be compromised by the plume signature of the missile launched from the platform. While reduced signature is desirable, it is usually obtained at the expense of performance.

Propulsion units and warheads must be available (cost and manufacturing, considerations) and work reliably after years of handling and storage. For example, the motor must burn stably, within the prescribed thrust-time envelope and with no increase in hazards when fired, regardless of its history.

HEDM must address each of these areas as they relate to one another. To accomplish a mission, trade-offs between performance, hazards, signature, and other factors must be made. For example, to achieve minimal signature propulsion, performance usually suffers. To regain performance, the operating pressure is often increased, which, in turn, often increases the hazards and combustion instability (thereby decreasing reliability). Future requirements have increased demands in each of these areas -- demands and trade-offs that can be addressed only through vigorous effort in this critical technology. New ingredients, manufacturing methods, and concepts have recently become available and must be exploited. The HEDM critical technology sets are shown in the following table.

Technology Sets in High Energy Density Materials

- Explosive Applications
- Propellant Applications
- High-nitrogen Atom Content Propellant & Explosive
- High-hydrogen Atom Content Propellant & Explosive

B. PAYOFF

1. Impact on Future Weapon Systems

Because it has widespread use in various weapon types and functional areas, and because it is a critical enabling technology, HEDM is a critical US technology. The development of future HEDM will enable the United States to continue to optimize:

- Minimum-signature, high-performance missile propellants (both for tactical and strategic use) with tailorable fast burn rates
- Warheads with higher lethality to decrease miss distances
- New generations of underwater explosives to maximize submarine structural damage
- High-performance shaped charges for increased penetration of armor and other hard targets
- High-performance launch vehicles and orbit transfer vehicles for space application
- New space-based high-speed kinetic energy kill vehicles
- Advanced low-vulnerability gun propellants giving increased range and damage to target
- Highly insensitive and threat-resistant nuclear weapons
- New pyrotechnically-actuated devices with increased speed and performance.

In addition to significant improvements of performance, the HEDM would provide less hazardous, less vulnerable, more reliable, and longer service life munitions.

Some specific goals and payoffs in HEDM, are given on the following page.

2. Potential Benefits to Domestic Industrial Base

While there is a significant industrial base providing HEDM, nearly all of the product is for the DoD, DoE, and NASA. Most non-military applications are NASA and communication satellite launch related. Other non-military applications (such as blasting agents) are not likely to be affected by the type of HEDM produced in this critical technology effort.

The US chemical industry forms a vital part of the industrial infrastructure for HEDM. Most forms of HEDM contain binders and energetic materials which greatly affect their working characteristics. Binders, which bond fuels and oxidizers together, alter the characteristics of HEDM in areas such as processing, curing, energy, energy release rate, and sensitivity. The properties of the binder generally determine the processing conditions that can be used to manufacture an energetic material.

Goals and Payoffs — High energy Density Materials

Application	Goal	Payoff
Propulsion		
Minimal-signature tactical missile propulsion	•Increase delivered performance over current observable motors •No visible or contrail signature •1,000% reduction in infrared signature •Radar cross section less than launch platform •No increase in hazards •No combustion instability •Tailorable burn rate	•Increased range (200 nm increases for anti-air, 500 nm for anti-surface), velocity (Mach 2 increase), and payload •Increased element of surprise and greater lethality •Reduced trackability and vulnerability •Reduced obscuration of own missile without increasing hazards or decreasing reliability
Boost propulsion for submarine-launched cruise missile	•Exceed current booster performance by 50% •Increased launch depth •Low signature plume	•17% increase in delivered boost performance yields 50% increase in range over existing Tomahawk cruise missile •Allow launch from greater submerged depth •Decrease ability to detect launch
Boost propulsion for strategic missiles	•Retain or exceed performance of current high signature metallized propellants •No primary or secondary plume signature	•Increased range, velocity, and payload •Increased amount of ocean to conceal submarine •Decreased risk of launch detection •Decreased risk to launch platform
High-energy gun propulsion	•Increased delivered performance over current gun propellant formulation •More than 50% increase in mass impetus •Greatly increased burn rates	•Increased range (stand off increase of 2 km) and velocity (200 m/s increase) without increasing hazards or decreasing reliability •Reduced vulnerability
Nonpolluting booster propulsion	•Exceed current performance by 100% •Clean propellant •Stable combustion	•Single stage to orbit •50% increase in payload •Affordable, on-demand launch system •No launch-site contaminations •Reduced atmospheric pollutants

Goals and Payoffs – High energy Density Materials (Continued)

Application	Goal	Payoff
Orbit transfer vehicle propulsion	•Exceed current performance by 100% •Clean propellant •Stable combustion	•100% increase in payload •50% reduction in launch costs •No vehicle contamination
	Explosives	
High-energy explosives for shaped charge application	•Increase penetration depth in steel armor plate -- 50% increase from the current formulations -- Meet insensitive munition requirements	•Increased armor penetration against thick armor increases vulnerable area of enemy tank •Increased safety, enhanced survivability
Bomb fill (blast/frag)	•Exceed performance of current fill •Meet IM requirements and/or 1.6 hazard classification •Affordable, producible materials and processes	•More munitions allowed in ready storage area, increasing number of sorties •Increased safety, survivability •No sacrifice in performance •Low cost
Underwater explosive technology	•100% increase in shock and bubble energy •Meet IM requirements	•Improved kill of current and future submarine and large surface vessels •Enhanced survivability
Booster technology	•Insensitive/high output booster explosives/devices for igniting insensitive explosives with large critical diameter	•Improved reliability in initiating insensitive HE materials (New devices increase reliability)
Follow-through and penetration warheads	•Survive hard-target penetration •50% increase in performance •Meet IM requirements	•In many cases provides difference from current no kill against hardened submarine, land, or ship targets
High-energy insensitive explosives for nuclear weapons application	•100% increase in performance •Reactive case •Meet IM requirements	•50% increase in missile range (smaller warhead) •Increased safety
Internal blast	•100% increase in performance •Reactive case •Meet IM requirements	•Kill ship and land targets •Increased missile range due to lighter warhead
Explosively formed projectiles	•50% increase in penetration •Meet IM requirements	•Effective against current and future armor threat •Increase safety, greatly enhanced survivability
Enhanced blast	•900% increase in blast energy over HE •Meet IM requirements	•500% increase in effectiveness against shielded targets •Low cost •Increased safety, enhanced survivability
	Pyrotechnics	
	•High output pyrotechnics with fast and tailorable burn rates •Ballotechnics	

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

Defense-related development plans for this critical technology focus on key issues in each of the following technology sets:

a. Explosive Applications

(1) Objectives

DoD requires new classes of explosives which are less sensitive to environmental effects (450 to 500 kilobar detonation pressure for shaped charges and EFP, 28 kilobar for bombs, 3500 to 4500 cal per gram chemical energy for underwater weapons) as well as explosive materials which provide high explosive energy per unit weight/volume (safe response to threats of cook-off, bullet, and fragment impact and sympathetic detonation). The objective is to develop higher performance, less hazardous materials that also have lower signature characteristics.

(2) Development Milestones

- CL20 and Trinitroazetidine (TNAZ) – High density C, H, N, O compounds are being developed as insensitive explosive fills for munition warheads with increased safety and survivability, no sacrifice in performance, and at a lower cost. Synthesis and scale-up of CL20 will be demonstrated in FY 1991, techniques for control of polymorphs and compatibility with binders will be identified in FY 1992, and application in weapons demonstrated by FY 1996. TNAZ will be scaled up in FY 1992 and demonstrated in weapon systems in FY 1995.
- CL20 and TNAZ are also being developed as more powerful explosives (i.e., more powerful than presently available). Both release significantly more detonation energy and can be used for increased armor and hard target lethality. CL20 is also being developed for underwater munitions for lethality enhancement. CAGE explosives – Highly dense strained C, H, N, O molecules are being designed and synthesized as more powerful explosives to achieve improved armor lethality. Tetranitrocubane, an intermediate toward the target octanitrocubane will be demonstrated in FY 1997. CL20 pressed applications will be demonstrated by FY 1994 and cast applications by FY 1996. CAGE scale-up will be demonstrated by FY 1992.

b. Propellant Applications

(1) Objectives

DoD requires new propellants with reduced signatures and lower hazards to the environment.

(2) Development Milestones

- Low Signature – Formulations containing TNAZ are being formulated and tested for low-signature military and non-military solid propellant applications (e.g., guns, rockets, missiles, and

SDI-related propulsion systems). One type of high energy liquid propellant (LP) candidate currently being investigated is based on a water soluble hydroxylammonium nitrate oxidizer and a caged molecule fuel such as a polynitrated adamantine derivative. Initial formulations of this LP will be made in FY 1992. Another type under investigation is variable viscosity liquid propellants which are based on dispersing solid oxidizers such as RDX in an energetic liquid. Liquid propellants are being developed for use in tank and artillery guns because they have higher energies per unit volume compared to solid propellants. Liquid propellant applications will be demonstrated by FY 1995. CL20 is being developed as a low signature, high performance tactical missile propellant and a high burn rate, minimum signature, high performance strategic missile propellant. Hexanitro ""-xaza Adamantine (HNHAA) — Propellant formulations are being developed for low signature solid fuel applications. Glycidyl Azide Polymer (GAP)-Hydroxy-terminated long chain polymer in propellant formulations with lower energy materials are being developed for low signature missile applications. Low signature HNHAA propellant applications will be demonstrated in FY 1995.

- Low Hazard — GAP formulations with nitrate esters maintain the required ISP for adequate rocket motor performance and are significantly less hazardous than current formulations. Gelled propellant formulations will be developed by FY 1993. Applications of GAP formulations will be evaluated for GAP during the FY 1993-FY 1995 timeframe.

c. Chemically Bound, Excited State Compounds

(1) Objectives

DoD needs the theoretical basis and tools for characterizing the performance of energetic materials in fuel, propellant, and explosive applications. Development of new HEDMs can be viewed as progressing along both evolutionary and revolutionary paths. The evolution path addresses nearer term needs through improvements in traditional organic-nitro chemistry. Increases in capabilities in this area will be measured in relatively small or moderate steps in performance and/or safety (as measured by insensitivity). Progress will depend heavily on improved basic understanding of the fundamental behavior of energetic molecules. Both experimental and theoretical techniques will require continuing development if projected improvements are to be realized. The revolutionary path addresses the few very high risk options available for large gains in HEDM capabilities. Examples include the production of high energy metastable states of materials, the construction of matrix composite energetics. These are long term efforts for which theoretical studies will dominate for a considerable time. Some investment in such revolutionary approaches must be sustained to hold open the possibility of significant gains in HEDM for the far term.

(2) Development Milestones

- Metastable solid states of matter characterized by large stored energy density, as potential fuels, propellants, and explosives are being identified using theoretical techniques. Tests will be conducted in FY 1994 to verify theory and scale-up demonstrated by FY 1996.

d. Nuclear Isomers

(1) Objectives

Nuclear isomers offer the potential of, and potential for, very high energy density. DoD plans are focused on proving the existence of, and potential for, such materials.

(2) Development Milestones

- Efforts are under way to verify the existence of high energy density materials that possess 10,000 to 1,000,000 times more energy than conventional explosives for applications in future advanced munitions. Tests under way will attempt to verify the existence of such materials by FY 1991 and, it round, isolate the isomer by FY 1995.

2. Technology Objectives

Technology Objectives – High Energy Density Materials

Technical Area	By 1996	By 2001	By 2006
High performance, minimal signature missile propulsion for tactical and strategic missile	• Scale up CL-20 and GAP synthesis • Development of minimal signature CL-20 propellant • Performance, hazard, and signature, stability assessment • Synthesize new ingredient (HNHAA or other if more promising) • Technology demonstraiton of class 1.3 propellants	• CL-20 small motor demo • Motors loaded with CL-20 transition to programs (anti-air-AAAM integral rocket ramjet, anti-surface, and strategic) • Scale-up HNHAA synthesis • Develop, characterize, minimal signature HNHAA propellants • HNHAA plume signature tests • Transfer GAP propellant to AMRAAM	• HNHAA small motor demo • Utilize HNHAA-based propulsion for new anti-air and anti-surface missiles, such as AAAM follow-on programs
High-penetration shaped charges	• High-explosive CL-20 and other new ingrediant manufacturing technology • High-energy explosive formulation based on CL-20 • Formulation optimization and scale up • Performance demonstration	• Shaped charge warhead/ liner design • Explosive qualification • Sensitivity assessment • HNHAA explosives development	• Anti-armor and hardened concrete penetration weapons for SMAW, Hellfire, AHWS (advanced helicopter weapon system), Dragon follow-on • HNHAA explosive evaluation
Low-vulnerability, high-energy gun propellant	• CL-20 or other new ingredient or high-energy gun propellant formulation • Propellant characterization and optimization • Performance demonstration (i.e., 20 mm cartridge PIP test)	• Formulation scale up • Hazard/sensitivity evaluation • Performance evaluation • Propellant qualification	• Type qualification, weapon evaluation and production for main battle tank and artillery
Blast warhead	• Subcaliber warhead evluation • Demonstraiton of bimetallic case/explosive concept	• Type qualification • Weapon evaluation for AAM and outer air battle missile	• Warhead production

Technology Objectives — High Energy Density Materials (Continued)

Technical Area	By 1996	By 2001	By 2006
High-shock and bubble energy underwater explosive	• Formulation design • New formulation (ionic oxidizer-metallized compositions) • Small-scale performance testing capability	• Formulation optimization and characterization • Evaluations of sensitivity, hazard, and performance	• New weapon design
Insensitive explosive fill for large munitions (advanced bomb family)	• Explosive candidate selection • Candidate scale up • Production of explosive • Compatible boosting technology • Type qualification	• Advanced bomb production	• Improved advanced bomb
Kinetic energy weapon (high-performance KKV propellant)	• Ingredient selection and formulation design (liquid; ClF_5, OF_2; metal = Be; Solid = CL-20 new burn rate modifiers) • Propellant characterization and optimization • Propellant scale-up • Performance demonstration	• Propellant scale-up • Processing studies (include environmental impact)	• Incorporate into kinetic kill vehicle
High performance/launch vehicles, and orbit transfer vehicles	• Technical demonstration of insensitive propellants – – Li in H_2 – ClF_5 0 – – FN_3/AP	• New insensitive propellant in launch system • Small motor demo of new species • Scale up of H atoms in H_2, K_1O species, HLi_3	• Full-size motors • Small motor demo of new species
Non-polluting booster propulsion for space application	• Evaluation of various propulsion concepts (clean, hybrid, or gelled liquid propellant) • Selection of candidate propellant • Propellant characterization and optimization	• Propellant scale up • Processing and manufacturing technology • Propellant qualification	• Configuration analysis • Propulsion system evaluation and production
Ballotechnics technology	• Ingredient selection • Formulation design/selection • Develop calculation codes • Small-scale testing	• Formulation optimization • Characterization • Energy release mechanism studies	• Performance demonstration • System design qualification • Weapon's evaluation and production
High-energy insensitive explosives for nuclear weapon	• Formulation design • Development of new formulation • Performance/sensitivity trade-off studies • Develop DDT and work-off models for cast explosives	• Formulation scale up • Performance evaluation • Hazard/sensitivity evaluation • Explosive qualification • Complete bench tests to benchmark DDT and work-off models	• Weapon evaluation and production

3. Resources

A summary of S&T funding[16] is shown in the following table.

Funding — High Energy Density Materials ($M)

FY87–91	FY92	FY93	FY94	FY95	FY96	FY97
409	84	86	95	93	96	98

All of the Services have significant development efforts supporting this critical technology.

4. Utilizing the Technology

Since most strategic and tactical weapons depend on rocket propulsion to reach their targets, the results of the HEDM critical technology development are needed in many future propulsion systems to increase performance (range, velocity, payload), decrease hazards, and decrease signature while providing increased dependability and reliability. Space applications (getting to orbit, orbit transfer, and kinetic energy vehicles) will also utilize the technology and will not have to rely on propulsion systems that produce highly toxic products.

Similarly, most conventional and strategic warheads utilize high-energy explosives in their design. Explosives based on HEDM are greatly needed to give increased detonation output (velocity and pressure) and decreased hazard sensitivity. Spin-off applications for short-wavelength lasers, air-breathing propellants, and very energetic fuels are distinct possibilities.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Existing Industrial Base Capabilities

The primary domestic manufacturing capability for energetic materials is contained within the DoD government-owned contractor-operated (GOCO) munitions production base. Substantial commercially owned energetics manufacturing facilities do exist; however, most of these facilities are highly dependent on government munitions and missile procurements.

HEDM manufacturing process technologies such as continuous mix, motionless mixers, and automated processes can significantly reduce investment cost for HEDM manufacturing.

2. Projected Industrial Base Capabilities

Implementation of new manufacturing technology for energetic materials, commercially or at GOCOs, involves procurement of selected energetic material from the private sector. Investment in energetics manufacturing capability will be defined by government industrial preparedness/mobilization policy, new energetics material introduced into production, and, finally, by the peacetime budgetary needs for energetic material-based system procurements, as a function of perceived readiness threats posed by the world situation.

16Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

DoD has, perhaps, its domestic greatest industrial base investment in the GOCO ammunition production base, which is dominated by energetics manufacturing facilities, either in the propellants and explosives (P&E) and pyrotechnics area or in energetic loading, assembly, and packout (LAP). Addition of robust capabilities for new advanced energetic materials, capability to satisfy newly identified product requirement, such as those for insensitive munitions and redefined environmental process requirements, will add to the need for both peacetime and mobilization-based investment in these facilities.

The primary commercial investments for DoD work in HEDM products and production are represented by the Contractor-Owned Contractor-Operated (COCO) facilities. DoD annually procures energetic-based ammunition and missile components having an approximate value in the $2 to $4 billion range.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

Although there is some mission and military hardware overlap among the military Services, the assigned missions of Army, Navy, and Air Force often dictate differing needs for energetic materials. However, there is excellent communication of results of basic research through advanced development between these DoD agencies, their DoE counterparts, and with industry. This largely occurs through groups such as the Joint Army-Navy-NASA-Air Force (JANNAF) Interagency Chemical Propulsion Information Group, the Working Party on Explosives, the Joint Logistics Commanders JCTG Groups, an annual HEDM conference, and DoD-DoE technical coordinating groups.

NASA, also interested in advances in propulsion for launching of space vehicles, has its own programs but communicates activities and results through the various JANNAF subcommittees and belongs to the HEDM Steering Group.

Diamond anvil cell technology, developed at NIST, is used to study the effects of very high pressure and temperature on the physical and chemical behavior of energetic materials of military interest. The pressure dependence of the temperature of thermal decomposition and the melting point can be measured as well as the delineation of phase stability fields which lead to pressure-temperature phase diagrams. The results of these pressure- and temperature-dependent kinetic measurements permit an improved understanding of the mechanism of decomposition, and are also used to define criteria which give relative sensitivities to the phenomenon of detonation. The results obtained from such measurements ultimately guide in the development of improved explosives and propellants.

NSF supports research on the preparation and reactions of high energy compounds, the mechanisms of their decompositions, and the characterization of reaction intermediates. Research is centered on strained-ring hydrocarbons, chemi-luminescent systems, and other high energy systems such as hydroperoxides, diazo compounds, and boranes.

2. R&D in the Private Sector

There is a significant capability for production of strategic and tactical propulsion units in the private sector (Thiokol, Aerojet, Hercules, etc.). These companies are heavily involved in developing new HEDM through their own IR&D efforts and through contracts with DoD agencies.

Production of explosives is done largely within DoD and DoE; very little private production of military type explosives occurs.

Significant basic research and exploratory development is occurring at various U.S. colleges and universities. This work includes synthesis studies and developing new diagnostic techniques.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

The table on the following page provides a summary comparison of the United States and other nations in selected key areas of high energy density materials. Ongoing international research and development indicates potential international capabilities to contribute to meeting the challenges and goals identified:

- Improved properties of insensitive high explosives
- Reduced observable signatures of propellants while maintaining or improving performance
- Improved modeling of energetic material reactions (three-dimensional, combined mechanical/chemical reaction properties)
- Application of energetic materials to ballotechnic processing.

The United States has the lead in the development of certain chemical explosives; however, countries such as France and the UK have the ability to match our accomplishments and can incorporate these materials into weapons as quickly, if not more so, than the United States. For example, both France and the UK have now synthesized CL–20, which was first synthesized in the United States in 1987. Primary opportunities for cooperation will occur with France and the UK for advanced HEDM work. Most other countries are not assessed to be actively engaged in the development of new explosives or higher energy density materials beyond the current production state–of–the–art materials such as RDX and HMX.

Production technology for most common energetic materials, such as nitroglycerine, nitrocellulose, and TNT, is widely available from a number of countries throughout the world. Certain countries, such as Italy and Switzerland, have an acknowledged lead in the production of nitroglycerine. The raw materials for the manufacture of these materials are widely available in every country with an established chemical process industry. At the present time, the French and British appear to have programs to develop new generations of HEDMs that are similar to chemicals currently under development and certification in the United States. These materials are approximately 20 percent more energetic than RDX and appear to have acceptable shock sensitivity and related parameters. There have not been any noticeable development efforts in other countries (allied or friendly) that would indicate a comparable program at this time; however, this assessment is based more on a lack of confirming data than specific data.

Development of energetic materials for both liquid– and solid–fueled missiles and rockets is widespread throughout the world. The French are now publishing their own textbook for the design and formulation of fuels for missiles, a clear indication of their progress in the missile age. Japan, Israel, France, the UK, Australia, Sweden, Norway, Canada, Germany, Italy, Switzerland, the Republic of Korea, Taiwan, Indonesia, India, and Pakistan all have programs for the development of solid–fueled and/or liquid–fueled engines for missiles and rockets. The relative accomplishments of these countries varies from state of the art to primitive. However, at this time the rate of advance is very rapid, and each of these countries has access to all of the necessary infrastructure and technological support to develop state–of–the–art HEDM, comparable to many currently under R&D programs in the United States.

Summary Comparison — High Energy Density Material

Selected Elements	USSR	NATO Allies	Japan	Others
Improve properties of insensitive high explosives	□□	□□□□ +	□□□ +	□□ China
Reduce observable signatures of propellants while maintaining or improving perfomance	□□	□□□ +	□□□ +	□□ China
Improve modeling of energetic material reactions (3-D, combined mechanical/ chemical reaction properties)	□□	□□□ +	□□□□ +	□□ China
Application of energetic materials to ballotechnic processing	□□□□ +	□□	□□	
Overall[a]	□□□ +	□□□ +	□□□ +	□□ China

[a] The overall evaluationl s a subjective assessment of the average standing of the technology int he nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□ broad technical achievement; allies capable of major contributions

□□□ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions

□□ generally lagging; allies may be capable of contributing in selected areas

□ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

\+ Foreign capability increasing at a faster rate than the United States

O Foreign capability increasing at a similar rate to the United States

— Foreign capability increasing at a slower rate than the United States

The Soviet Union has an extremely large R&D program for the development of HEDM, which in some respects is more advanced than that in the West. In fact, the Soviets have made investments in several areas for which comparable programs do not exist in the West. In particular, the Soviet Union is perceived to be ahead of the United States in the areas of insensitive high explosives development and ballotechnic formulations.

2. Exchange Agreements

Energetic materials have long been the subjects of international agreements. The Technology Cooperation Program (TTCP) also provides exchange mechanisms through a number of activities in conventional weapons.

All of the Services have a number of data and information exchanges with NATO allies as well as with a few other nations. Topics range from basic physics of materials and detonation to application of materials as explosives, propellants (both guns and rocket motors), reactive armor, and pyrotechnics and logic devices in safing, arming, and fusing devices. There are also exchanges on safety and disposal. In addition, the United States has agreements with a number of non-NATO allies in both basic materials and selected applications.

The area of high energy density fuels for air-breathing propulsion is also integral to, and is an aspect of, exchange under agreements relating to air-breathing propulsion.

18. COMPOSITE MATERIALS

18. COMPOSITE MATERIALS

A. DESCRIPTION OF TECHNOLOGY

The creation of new structural materials is revolutionizing the development of vehicles, buildings, systems and components, and structures around the world. Composite materials technology also promises significant improvement for weapons performance, design, and affordability. Furthermore, composite materials have broad dual-use applications in industry and the military. These factors combine to warrant the selection of composite materials as a critical technology.

Composite materials are defined as two or more constituent materials that are combined together in such a manner to produce a substance possessing selected properties superior to those of its individual components. Composites generally consist of fibrous or particulate reinforcements held together by a common matrix material. Composites are classified by their matrix material. Continuous fiber reinforcements enhance preferred direction structural properties of a composite.

Composite materials are important to the design and manufacture of many present and future military systems. For some systems, composites are recognized as the enabling technology required for fulfillment of demanding thermal, structural, and mechanical requirements (such as for the National Aero Space Plane (NASP), advanced gas turbines, deep submergence vehicles, spacecraft, and long range cruise missiles). Highstrength/light-weight composite materials are essential to many other critical military applications as well.

Specific defense-related research and development plans in this critical technology area are centered on the most pervasive and important matrix materials and their fibrous reinforcements, namely Organic (Polymer) Matrix composites (PMC), Metal Matrix Composites (MMC), Carbon Matrix Composites (C/C). Ceramic Matrix Composites (CMC), and a variety of hybrid composites. Technology development and research thrusts in this critical technology area are directed at key issues and are designed to expand the use of composite materials for even wider defense applications. Such issues include: improving the fiber-matrix chemical interface (to prevent degradation of the composites); developing superior coatings technology (especially for improved corrosion and oxidation resistance); improving structural analysis (to better understand the failure mechanisms, fatigue, strain, and life-cycle factors of these complex materials); advancing fiber manufacturing technology (to explore better fiber structures, coatings, and weave techniques); and improving matrix manufacturing processes (such as rapid solidification techniques for metals and powders and plasma flame spraying techniques). The table below summarizes the technology sets for this critical technology.

Technology Sets in Composite Materials Technology

- Polymer (organic) matrix composites
- Metal matrix composites
- Carbon matrix composites
- Ceramic matrix composites
- Hybrid composites

B. PAYOFF

1. Impact on Future Weapon Systems

Composite materials technology affects virtually every new weapon system. These materials will be needed to make future systems most effective in a wide spectrum of vehicle structures, including: high-temperature propulsion systems; hypervelocity vehicles; short take-off and landing (STOL) and vertical take-off and landing (VTOL) vehicles; as well as for spacecraft, protection against directed energy threats; and advanced hull forms and submarine structures. Next-generation composite materials and structures will emphasize additional multi-function capabilities (which integrate sensors and countermeasures), resulting in options for military systems that are unheard of today. Advanced composite materials will fulfill the needs of the following series of weapon systems type requirements:

- Damage-tolerant composite materials and hardening concepts for protection of platforms and weapons systems against operational hazards and advanced threats
- High thermal-conductivity materials for critical thermal management applications such as heat dissipation from electronic devices, infrared signature suppression, and weight-efficient radiators
- Thermostructural composite materials for improved efficiency and reliability of advanced propulsion systems (gas turbines, air-breathing missile motors, rocket nozzles)
- Submarine system composite materials for improved capabilities in depth, speed, and covertness, and for cost reduction
- Erosion-ablation-resistant composite materials for all-weather capability and improved performance of missiles
- Electromagnetic absorbent hybrid composite materials having sufficient strength and stiffness to serve as useful structural members for aircraft, ships, and missiles (non-parasitic).

Advanced composite materials technology offers opportunities for substantial improvements in performance, reliability, and reductions in life-cycle cost. The ongoing demonstration of a PMC armored-vehicle turret and hull will help lead to the broader adoption of these components to a family of ground vehicles, where weight savings of 25 to 50 percent can be achieved with accompanying cost savings. High-temperature composite materials are one of the enabling technologies to increase engine thrust by more than 50 percent and reduce fuel consumption by as much as 40 percent. The use of new high thermal conductivity composites in electronic device components can reduce the thermal resistance between chip and heat sink by 15°C, affording a 50 percent increase in reliability. Multi-functional hybrid composites can reduce the gross lift-off weight on an intercontinental cruise missile by a factor of 4 or more.

2. Potential Benefits to Industrial Base

The current value of components produced from advanced composites in the United States is less than $2 billion per year. Sales projections through the year 2000 are highly variable, ranging from $5 billion to $20 billion per year. This estimate includes only the value of the materials and structures; it does not include the value of the finished products, whose performance, and therefore competitive posture, is improved by use of the materials. When the overall value of these products is taken into account, use of advanced structural composite materials is likely to have a dramatic effect on gross national product, balance of trade, and employment.

Military demand for high-performance materials in the United States has already created a thriving community of advanced materials and equipment suppliers bolstering domestic strength in the manufacture of composites fabrication and inspection equipment. For example, the U.S. currently has extensive capabilities for the production of processing equipment used for the manufacture of polymer matrix composite structures. U.S. firms supply a variety of equipment such as tape layers, filament winders, plycutters, and pultrusion machines. Other important domestically produced equipment includes plasma sprayers, manual and computerized x-ray machines, and radiographic and computer-aided axial tomography (CAT scan) equipment. One area of concern is U.S. industry's reliance on foreign sources for some types of equipment, including: specialized heat treating furnaces; powder-making equipment; computer-controlled hot rolling mills; hot isostatic presses; robots; and three-dimensional weaving machines. Furthermore, U.S. suppliers of composites processing equipment could be affected by a downturn in military spending, which has represented a major source of their sales revenue.

These suppliers are seeking to expand commercial applications for their materials. At present, though, advanced materials developed for military applications are expensive relative to the commercial sector, and fabrication processes are poorly suited for mass production. However, great promise for the commercial application of these materials is foreshadowed by current specialty applications in the commercial sector.

For example, organic matrix composites currently are used widely in commercial aircraft, recreational equipment (racquet sports, golf clubs, fishing rods, windsurfers), commercial satellites, refrigerator liners, and washing machine tubs. Carbon-carbon composites are used in commercial aircraft brakes and race car brakes, prosthetics in humans, furnace components, truck pistons, and the NASP Project.

Furthermore, by the year 2000, composites could make up 50 percent of structural weight of commercial transport aircraft. Estimating a structural weight of 75,000 pounds per aircraft and production of 500 aircraft per year, this application alone should account for 24 million pounds of advanced composite per year. Assuming a starting material value of $60/lb, the market in the year 2000 is estimated to be approximately $1.5 billion for the composite material alone. (A more conservative estimate, which assumes that no new commercial aircraft will be built by 1995, has placed the U.S. composite commercial airframe production at between 1 and 2 million pounds during that year.)

Potential use of composite materials in commercial structures (as a reinforcement material) also could enable the construction of bridges, highways, sidewalks, and large buildings with enhanced structural capabilities, possibly eliminating many corrosion problems. This could result in bridges lasting 100 to 200 years, versus 35 to 75 years today. Roadways and walkway surfaces could be made resistant to cracking caused by temperature changes, road salt, or deicing compounds. Automobile industry use of composites in vehicle frames, as well as for bodies and engine components, could lead to high efficiency transportation with a potential for the wholesale recycling of parts.

Still, potential U.S. commercial end users believe that major use of these materials will not be profitable within the next five years, the typical planning horizon of most firms. In many cases, 10 to 20 years will be required to solve remaining technical problems and to develop rapid, low-cost manufacturing methods. Investment risks are especially high for commercial end users because the costs of scaling up laboratory processes for production are enormous, and the rapid evolution of technology could make these processes obsolete. Hence, there is little commercial incentive for advanced materials technologies in the United States.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

The defense-related composite materials development plan is centered on the five major technology sets described below. These thrusts offer large potential payoffs for the future and are aimed at developing fundamental knowledge of the processing, structural property relationships, failure mechanisms, characterization, and life prediction (and nondestructive evaluation) of these materials.

a. Polymer (Organic) Matrix Composites

(1) Objectives

The major objectives for this technology set are to: (1) develop alternative materials and manufacturing processes that provide organic matrix composites and components with improved performance and cost effectiveness to meet future DoD mission requirements; (2) incorporate concurrent engineering, design, and producibility into materials and manufacturing processes; and (3) develop a focused mechanism for transitioning and supporting new organic matrix composites rapidly into production applications.

(2) Development Milestones

Major milestones contributing to the achievement of the objectives in this technology set include:

- Evaluating new moisture-resistant resins, ordered polymers, conductive polymers, thermoplastics, fiber sizings, and high-temperature adhesives (FY 1993).
- Developing fibers with improved strain-to-failure and non-circular cross sections (FY 1994).
- Developing modeling components, woven preforms, and unidirectional tape and fabric (FY 1994).
- Improving mechanical fasteners and thermoplastic forming methods (FY 1995).
- Developing CIA design optimization routines (FY 1995).
- Developing quality assurance methods, internal sensors, and frequency amplitude reflection methods (FY 1996).
- Identifying CAM/CIM low cost manufacturing and processing methods and scale up to large system sizes (FY 1996).
- Establishing methods for repair in space, repair of battle damage, and RAM/RAS repair (FY 1997).

b. Metal Matrix Composites

(1) Objectives

Metal matrix composites (MMCs) are an emerging technology critical to the future of the United States industrial base. The objectives of this technology set are to develop materials combinations and manufacturing processes to produce MMCs with a high level of reproducibility and cost effectiveness and to better integrate these new materials into existing and future DoD systems.

(2) Development Milestones

Major milestones contributing to achieving the above objectives in metal matrix composites include:

- High strength reinforcement fibers, SiC particulate and whiskers, ceramic, and boron carbide fibers (FY 1992).
- Matrices for high thermal conductivity and high temperature applications (copper, aluminum, titanium, superalloys) (FY 1993).
- Low cost directed motal oxidation (Lanxide® process).
- Component manufacturing, shear spinning, joining and high speed machining (FY 1994).
- Reduce the cost of continuous fiber reinforced metal matrix composite sheet by 10 times via MMC Model Factory (FY 1995).
- Quality assurance, non-destructive inspection; CAI/AI process controls (FY 1996).
- Component repair, repair in space, joining of structural elements (FY 1997).

c. Ceramic Matrix Composites

(1) Objectives

Ceramics are a class of materials exhibiting high elastic modulus, very high temperature and corrosion resistance, and high hardness. Objectives of this technology are to develop reinforced ceramics with: significantly improved toughness compared to monolithic ceramics; low sensitivity to point defects; high strain-to-failure characteristics; and reduced susceptibility to catastrophic failure. Another objective is processing automation and subsequent reduced cost of fabrication.

(2) Development Milestones

Major developmental milestones needed to achieve these objectives include:

- Improve temperature capability of ceramic fibers from 2200°F (FY 1996).
- High yield polymers for conversion to ceramic matrices, mullite, zirconates (FY 1993).
- High strength ceramic fibers and whiskers, boron nitride, boron carbide, hafnium carbide, etc. (FY 1994).

- Process development, low cost castings, hot isostatic pressing (hipping), microwave sintering, CVI (FY 1994).
- Laser machining, near-net-shape manufacturing, low cost processing (FY 1995).
- Non-destructive inspection and evaluation, micrometer flow detection, CAI process controls (FY 1995).
- Repair of ceramic matrix composites, joint fabrication, bonding of ceramics (FY 1996).
- Design, reliability analysis, computer integrated engineering (FY 1997).

d. Carbon-Carbon Composites

(1) Objectives

Carbon-carbon composites offer significant potential applications in a variety of defense and commercial applications. Major defense-related objectives for developing this technology include: demonstrating the advantages of carbon-carbon composites in applications where property retention (strength, modulus, ablation resistance) is required at very high temperatures (3,000-5,000F), and developing oxidation protection systems that effectively protect the fibers and matrix in oxidative and atomic oxygen environments.

(2) Development Milestones

Major developmental milestones needed to achieve these objectives include:

- Developing high char-yield precursors for conversion to high density carbon matrices (FY 1993).
- Demonstrating "hybrid" impregnation processes to provide shortened densification cycles (FY 1994).
- Synthesizing fiber sizings and surface treatments to facilitate weaving and processing of fiber preforms (FY 1995).
- Developing oxidation protection systems that are reliable, consistent, and durable in a variety of temperature and environmental exposures (FY 1996).
- Demonstrating performance improvements in turbine engine components, hypervelocity vehicles, and spacecraft thermal shields (FY 1997).

e. Hybrid Composites

(1) Objectives

Hybrid composites offer significant potential applications in a variety of novel situations. Defense-related objectives in this technology set focus upon identifying and demonstrating the advantages of composite "designs" combining multiple constituents (fibers, polymers, metals, non-metals) to achieve optimum properties tailored for specific performance goals.

(2) Development Milestones

To achieve these objectives, the following milestones are needed:

- Initiate a design data base for hybrid composites (FY 1992).
- Characterize complex constituent interfaces (FY 1993).
- Generate thermo-structural analysis methods for complex hybrid systems (FY 1994).
- Develop joining technology for complex systems (FY 1995).
- Identify quality assurance criteria (FY 1996).
- Generate standardized inspection techniques (FY 1997).
- Initiate production scale-up (FY 1997).

2. Technology Objectives

Technology Objectives — Composite Materials

By 1996	By 2001	By 2006
• Development of high-temperature metal, ceramic, and carbon composite engine components • Pervasive application of composite materials in aerospace vehicles and advanced ship/submarine hulls and land vehicles	• Qualification of composite materials for thermal management and weight reduction in electronic devices and space vehicles • 25 to 50% weight reduction in airframes, land vehicles, and space vehicles • Significant reduction in radar and infrared signatures • Thrust-to-weight ratio for gas turbine engines increased to 17:1	• Widespread use of advanced composite materials in US weapons systems and platforms • Thrust-to-weight ratio for gas turbines achieves 20:1 • Composite fabrication conducted in space

3. Resources

Army, Navy, Air Force, and DARPA are the principal performers in this critical technology. Each Service focuses its development programs on those composites critical to meeting system performance requirements.

A summary of total S&T funding[17] for this critical category is given in the following table.

[17]Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity. Here the NASP is not included.

Funding — Composite Materials ($M)

FY87-91	FY92	FY93	FY94	FY95	FY96	FY97
1089	193	197	211	218	224	229

4. Using the Technology

DoD's effort in high-performance structural materials technology continues to affect virtually all major weapons systems (fixed-and rotary wing-aircraft, spacecraft, missiles, and ground and sea-going vehicles).

Polymer matrix composites are the most mature composite technology. Beginning in the 1970s, composites were used in military applications (such as fighter aircraft and rocket motor casings), and they now have a solid record of exceptional performance and reliability. Composites rapidly are becoming the baseline structural material of the defense aerospace industry. This sector has been estimated to consume as much as 80 percent of all high-performance PMCs. Growth projections for aerospace use of composites have ranged from 8.5 percent per year to 22 percent per year. The primary matrix materials in aerospace applications are epoxies, and the most common reinforcements are carbon/graphite, aramid (e.g., Kelvar 49), and high-strength glass fibers. However, high-temperature thermoplastics (such as PEEK) are considered by many to be the matrices of choice for future aerospace applications. Composites are used extensively today in small military aircraft, military and commercial rotorcraft, and prototype business aircraft. The next major aircraft market opportunity for composites is in large military and commercial transport aircraft.

The principal advantages of PMCs in aerospace applications are their superior specific strength and stiffness compared with metals, resulting in weight savings of 10 to 60 percent over metal designs (a 20 to 30 percent weight saving is typical). This weight reduction can be used to increase range, payload, maneuverability, and speed or reduce fuel consumption. A pound of weight saved on a commercial transport aircraft is estimated to be worth $100 to $300 over its service life, depending on the price of fuel, among other factors. This high premium for saved weight is unique to the aerospace industry, which is why aerospace applications of PMCs lead all other applications in growth rate. Additional advantages of PMCs are their superior fatigue and corrosion resistance and vibration damping properties.

Manufacturing capabilities for ceramic matrix composites are not nearly as advanced as for polymer matrix composites. However, one recent innovation in producing fiber-and particulate-reinforced CMC's by directed oxidation of molton metals has reached a commercial stage with DARPA support. This Lanxide® process has produced ceramic composite tile for applique armor and is nearing development of ceramic composites for automotive applications.

Advanced composites are essential to the superior performance of a large number of fighter and attack aircraft. Composites may account for up to 40 percent of the structural weight of the Advanced Technology Fighter (ATF), which is still in the design phase. Because the performance advantages of composites in military aircraft more than compensate for their high cost, the military market is likely to be the fastest growing market for advanced composites during the next decade. One estimate, which considers existing production and the ATF, projects a growth from about 0.3 million pounds per year in 1985 to 2 million pounds per year in 1995.

If glass fiber reinforced composites are included, the volume of composites used in commercial and business aircraft is about twice that used in military aircraft. In current commercial transport aircraft, composites make up about 3 percent of the structural weight and are used exclusively in the secondary (not flight-critical) structure. However, several companies utilize composites in the wings, empennage, and fuselage of business aircraft.

With the exception of the all-composite business aircraft prototypes, which are in the certification process, composites have been used more extensively in helicopters than in aircraft. Military applications have led the way, and the advantages of composites are much the same as in aircraft: weight reduction, parts consolidation, and fatigue and corrosion resistance. During the past 15 years, composites have become the baseline materials for rotors, blades, and tail assemblies. Future military helicopters, such as the Army's LHX or the Navy's tilt-rotor V-22 Osprey, have specifications that force designers to consider composites, which are likely to comprise up to 80 percent of the structural weight. Materials such as graphite/epoxy are likely to be used in the airframe, bulkheads, tail booms, and vertical fins, while the less stiff glass/epoxy composites will be used in the rotor systems. As with aircraft, there could be a long-term trend away from epoxy resins and toward thermoplastic resins.

Composites of all types, including ceramic, polymer, and metal matrix composites, are ideal materials for use in space-based military systems, such as those associated with the Strategic Defense Initiative (SDI). Properties such as low density, high specific stiffness, low coefficient of thermal expansion, and high-temperature resistance are all necessary for structures that must maneuver rapidly in space, maintain high dimensional stability, and withstand hostile attack.

Continuous ceramic-fiber metal matrix composite manufacturing will reduce the cost of MMC's by a factor of 10 by FY 1995. The DARPA-supported MMC Model Factory being developed by 3M Corp. will produce continuous 2-feet wide MMC sheet using a technique involving vapor deposition of alloys onto ceramic fibers in a spread tow.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

a. Current Manufacturing Capabilities

During the past decade the composites industry has emphasized the importance of new and improved composites manufacturing capability as a critical need for expanded application of composites materials. As a result, many cost-reducing manufacturing techniques have been introduced, through automation of the lay-up, handling, and cure of composite materials. One such automation activity is the development of tape lay-down machines, which nearly eliminate the hands-on labor for this operation and increase material lay-down rates up to 10 times that of hand lay-up. However, tape lay-down machines only work on parts that are flat or gently contoured. Laminate part quality improvement with less rejects has been achieved. Other automated techniques developed and being used include a complete ply laminator and robotic lay-up of plies. Several major aerospace companies have established (or have under development) complete composite fabrication centers that include a high degree of automation, ranging from incoming materials inspection to lay-up, cure, and assembly. Recent DoD manufacturing technology investments include adhesively bonding composite materials, producing thermoplastic secondary aircraft structures, reducing cost of fuselage composite components and structures, and improving techniques for nondestructive testing of composite materials.

b. Current Logistics/Support Capabilities

Because of their investments in high performance aircraft production capability, the Air Force has been the primary logistics leader of composite materials manufacturing technology followed by the Navy. The Army has the lead in the development of high performance composites for ground vehicle applications.

Logistics capabilities will improve dramatically as lower weight airframes, ground vehicles, and towed weapons become more air-transportable. Advanced composite materials have been instrumental in lowering the weight of Army weapon systems, while maintaining or improving performance/ruggedness. Portable bridging fabricated primarily from composites will provide support for troops and vehicles over longer spans. Individual soldier combat armor and gear using composite materials will reduce weight 20 to 30 percent, while improving mobility under an increased number of threats. Other examples of composites used run the spectrum from small navigation gyros for ground vehicles and missiles, to composite rotor blades of current and future helicopters such as LH. Composites are inherently capable of novel designs that typically reduce part count and assembly costs. Superior durability/fatigue tolerance, corrosion protection, low radar cross section, and chemical resistance are other attributes recognized by the Army for new applications. Maintenance logistics must be modified to accommodate field repair needs.

The logistics infrastructure for U.S.-based production of raw material feedstocks of thermoplastic and thermosetting resins, as well as most reinforcing fibers, is the best in the world. The majority of high-volume domestic composites manufacturing takes place throughout the automotive industry, where Resin Transfer Molding (RTM) and Resin Injection Molding (RIM), as well as injection molding and transfer molding of reinforced plastics, are common. The materials used are mostly commodity resins and discontinuous reinforcements. Modifications to existing manufacturing hardware, including tooling, and military/commercial investment in new automated production equipment compatible with the inherent idiosyncracies of fiber/resin forms and degree of tack (such as "towpregs," prepreg roving, and various width tapes) will provide great improvements in high volume fraction, continuous-fiber end items with superior strength/weight ratios.

Defense-related efforts need constant interaction with industry. Three examples of this interaction at the separate Service level are the Navy's new Center of Excellence for Composites Manufacturing Technology (CECMT) consortium of over 70 companies and universities, the Army ManTech Thrust Areas, and the Air Force Structural Materials Manufacturing Initiative (SMMI) addressing specific technology barriers in composites and adhesives common to DoD. Each specific manufacturing barrier addressed would be applied to end items of each Service branch, providing greater leverage and participation toward reaching its goals, as well as far more implementable technology transfer for investments made by each Service.

2. Projected Industrial — Capabilities

a. Projected Manufacturing Capabilities

Even using the most advanced manufacturing techniques and equipment available, composites typically are being applied only when system performance gains (i.e., fighter aircraft and stealth characteristics) justify the additional cost. Future aircraft must be designed with composites and automation in mind if the full benefit of the technology is to be realized. Composites use is dependent on affordability which is driven more by producible designs than by automation of a "black aluminum" design. Future manufacturing capabilities must address these concerns.

Each of the military departments is pursuing manufacturing developments of PMC to improve quality and reduce cost. These new developments have been made available to the entire aerospace industry. Also, renewed composite application interest by NASA for commercial aircraft (High-Speed Civil Transport (HSCT)) has resulted in some new design and manufacturing development programs.

The basic composite material industries (fiber and resin) are vital to maintaining and increasing the composites industry and have responded quite well to national interests in maintaining a lead position in composites manufacturing. Projected future development will require increased coordination between composite process equipment manufacturers and their material suppliers.

b. Projected Logistics/Support Capabilities

One of the major logistics and technical hurdles to be overcome in composites processing is the need to replace manual hand layup operations with truly reliable automated layup machine tools capable of covering moderate/high curvatures over large areas. This will require continued investment in robotic broadgoods dispensing equipment, software, and tooling in order to meet future output and surge capacity requirements. A recently completed Board of Army Science and Technology (BAST) study has provided a means to identify and review specific composite processing technology barriers that tie directly to logistics/support/technology transfer. Among future manufacturing technology projects that support composite materials processing are:

1. Advanced Tooling Technology for Composites Production
2. Fiber Placement Technology
3. Maximizing the Efficiency of Manual Layup of Composites
4. Advanced Artificial Intelligence (AI) Composite Curing
5. Preform Manufacturing Technology
6. Resin Transfer Molding (RTM) for Large Structures
7. Composite Repair Manufacturing Technology
8. Electromagnetic Pulse/Interference (EMP/EMI) Shielding
9. MFG, Vision Inspection/NDE System for Composite Parts
10. Laser Cutting and Machining of Composites.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

Composite materials research and development is underway at NASA, DoE, Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Oak Ridge National Laboratory (ORNL), and the Sandia Corporation. In addition, composite materials work is also underway at the Department of Commerce (DoC)/National Institute for Science Technology (NIST) and to a lesser degree under the sponsorship of the National Science Foundation (NSF). NASA high-temperature composite materials work is tightly coordinated with DoD NASP and Integrated High Performance Turbine Engine Technology (IHPTET) programs through coordinating groups. NASA composite materials work related to advanced civil transports is also coordinated with DoD through conference coordinating groups such as the DoD/NASA/Federal Aviation Administration (FAA) Conference on Fibrous Composites in Structural Design.

The bulk of the current NIST composite efforts is a major program on polymeric composites for mass-market, civilian applications. The objective of the NIST program is to provide industry with generic science and technology to reduce fabrication costs and increase capabilities for predicting performance. The program is divided into three task areas: processing science, microstructure characterization, and laminate properties. Smaller NIST programs focusing on metal matrix and ceramic matrix composites are also underway. The NIST metal matrix composite effort is directed toward understanding the process of high-speed electro-deposition of alloys and intermetallics with near-atomic scale control of interface composition. For ceramic matrix composites, the current NIST emphasis is on understanding toughening mechanisms, fracture behavior, and the role of residual stresses during processing.

NSF supports materials research related to composites, ceramics, polymers, metallurgy, and electronic and biological materials. Support is provided primarily through ongoing programs in materials science, engineering, and computer sciences. In addition, two NSF centers conduct research in areas related to composite materials. The Center for Interfacial Engineering focuses on thin-film processing, coating process fundamentals, polymer microstructures, surfactancy and self-assembly processes, and characterization and behavior of interfaces. The Center for High Performance Polymeric Adhesives and Composites focuses on research at the molecular, micromechanical, and interfacial levels to allow predictions of macroscopic behavior.

Key NASA tasks include: development of advanced composite materials for airframe applications up to 600F; development of innovative design concepts; verification of fabrication processes for cost-effective structures; and validation of sub-scale and largescale advanced composite components. Advanced materials, including toughened thermosets and high-temperature thermoplastic composites with improved processability, will be developed for long-term use from 350F to 600F. Innovative design concepts and fabrication methods; (e.g., integrally stiffened fuselage and wing structures using costeffective manufacturing methods including filament winding, pultrusion, and hot pressing) will be developed for advanced airframe structures. Critical composite elements and subcomponents leading up through large-scale structures will be designed, fabricated, and tested to develop the data base required for design of primary airframe structures. Advanced structural analysis and life prediction methods will be developed and verified to establish a certification methodology for composite airframe structures. NASA's composites program goal for propulsion applications is increased fuel economy, improved reliability, extended life, and reduced operating costs. Key to the success of the program is the development of a technology base for advanced materials for use from 450F to 3000F such as metal matrix and intermetallic matrix composites, ceramic matrix composites, and high-temperature polymer composites. This activity focuses on fundamental research on: advanced fibers, materials, and processes; fabrication concepts; high-temperature test methods and sensors, design, and analysis methodologies for composite materials; and life prediction methods leading to the design, development, and test of critical propulsion components.

Overall, most of the R&D on high-temperature composite materials is under way in NASA and DoE laboratories, whereas the lower temperature PMC R&D is being conducted at DoC/NIST and NSF, as well as at NASA and DoE.

2. R&D in the Private Sector

Research and development is proceeding in all aspects of composite materials in industry, universities, and government laboratories. Research areas that are most prevalent are low-cost manufacturing processes and optimization of structures.

The potential for advanced materials in the manufacturing sector will not be realized unless and until companies perceive that their criteria for investment in R&D and production will be met. Investment criteria used by advanced materials companies vary depending on whether they are materials suppliers or users, whether the intended markets are military or commercial, and whether the end use emphasizes high materials performance or low cost.

Suppliers of advanced structural materials tend to be technology driven; they are focused primarily on the superior technical performance of advanced materials and are looking for both military and commercial applications. Suppliers tend to take a long-term view, basing investment decisions on qualitative assessments of the technical potential of advanced materials. On the other hand, users of advanced materials tend to be market driven; they are focused primarily on short-term market requirements, such as return on investment and time to market. At the present time, Japan leads the world in the production of ceramic reinforcing fibers. The U.S., however, is making excellent progress in developing oxide and nitride fibers.

Extensive use of PMCs by the automotive industry would bring about completely new industries, including a comprehensive network of PMC repair facilities, molding and adhesive bonding equipment suppliers, and a recycling industry based on new technologies. Current steel vehicle recycling techniques will not be applicable to PMCs, and cost-effective recycling technologies for PMCs have yet to be developed. Without the development of new recycling methods, incineration could become the main disposal process for PMC structures. The lack of acceptable recycling and disposal technologies could translate into higher cost for PMC structures relative to metals.

Numerous universities have established composite centers (e.g., the Center of Excellence on Manufacturing Science of Composites at the University of Delaware). Additionally, the Great Lakes Composite Consortium (GLCC) has been recently established as a Center of Excellence for Composites Manufacturing Technology. Here, research is aimed at combining manufacturing science and engineering design with an emphasis on building quality into thick section composites typically used in military applications. Materials forms being investigated include both thick section laminates and textile woven forms using thermosetting and thermoplastic matrix materials. Particular emphasis is being given to cure sensing and in-process control fabrication of thick section composites, thermal and mechanical characterization, structure-property relationships, and methods for nondestructive testing.

Additional research in the university community includes DoD-funded investigations of micro-mechanics processes, continuum to the atomic scale, tailoring of mechanical behavior through appropriate chemistries at the composite interface, process mechanics (in metal matrix composites), and fracture mechanics.

F. INTERNATIONAL ASSESSMENT

1. Technology Base and Industrial Base

The table on the following page provides a summary comparison of the United States and other nations in selected key areas of composite materials. Ongoing international research and development indicates potential international capabilities to contribute to meeting U.S. challenges and goals including:

- Development of composite materials capable of retaining structural properties at high temperatures
- Application of structural composites to reduce observables
- Development of improved nondestructive evaluation techniques for advanced composites
- Improved characterization of composite material response to weapon effects
- Improved modeling and prediction of life cycle failure.

Both Japan and NATO have active materials development programs and may lead in selected aspects of research. The United States has an overall lead, however, in the design and effective use of advanced composite materials in specific military applications. Primary opportunities for cooperation with Japan will occur in the area of ceramics and, with NATO countries, in the area of ceramic composites for jet engine hot sections and, perhaps, in selected processing technologies. These countries are also actively pursuing the application of advanced composite materials to robots for industrial and other uses (e.g., space robots).

The allies typically follow the U.S. lead in the application of advanced materials to military systems, but the use of composites is now well established in every country with a significant arms industry, and other nations may lead in commercial applications. The industrially advanced West European countries and Japan have established themselves as important suppliers to the United States. Japan is embarking on a major initiative in materials to support development of next-generation air transports. Their stated intent is to establish a center for research and development of new materials for use at temperatures as high as 2000C.

The French are among the world's leaders in production of ceramic composites and have embarked on a joint venture with a major U.S. company. As in the United States, there is considerable interest in attaining higher turbine inlet temperatures to increase engine performance utilizing those materials. In addition to France, the UK, Germany, and Japan are active in the field. An active research program in materials research is also under way at the Swiss Ecole Polytechnique Federale de Lausanne. The materials science department there draws scientists from France, Germany, the UK, and Italy in about equal numbers. The international nature of research appears typical of much of the present materials research within NATO. These programs could be strengthened further with European unification in 1992. In materials and structures R&D, the Soviet Union is second to only the United States and Japan.

Because of the need for improved military capability, composite materials are being designed into a variety of U.S. military equipment. More widespread use of these materials is expected to occur in the near term. Composite materials are also beginning to appear in foreign military equipment. The United States is judged to have the world leadership in composite materials. This lead is being rapidly eroded, however, by a combination of industrial technology transfer, such as is now occurring in aircraft composite technology, and strong R&D efforts by many other nations.

Many of the newly industrialized countries, particularly in the Pacific Rim, are expected to direct a significant portion of their R&D and manufacturing resources to weapon

Summary Comparison – Composite Materials

Selected Elements	USSR	NATO Allies	Japan	Others
Development of composite materials capable of retaining structural properties at high temperatures	□□□ ○	□□□ +	□□□ +	
Application of structural composites to reduce observables	□□	□□□ ○	□□	□□□ ○ Israel
Development of improved NDE techniques for advanced composites	□□	□□□ ○	□□□ ○	
Improved characterization of composite material response to weapon effects	□□□ ○	□□□ ○	□□	
Improved modeling and prediction of life cycle failure	□□	□□□ ○	□□□ ○	
Overall[a]	□□	□□□ ○	□□□ ○	□□ Israel

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

- □□□□ broad technical achievement; allies capable of major contributions
- □□□ moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
- □□ generally lagging; allies may be capable of contributing in selected areas
- □ lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend Indicators – where significant or important capabilities exist (i.e., 3 or 4 blocks):

- \+ Foreign capability increasing at a faster rate than the United States
- ○ Foreign capability increasing at a similar rate to the United States
- – Foreign capability increasing at a slower rate than the United States

systems due to the high profits to be realized from military sales. These countries are expected to establish a strong infrastructure to produce composite materials in support of this industry.

Advanced structural materials industries have become much more international in the past several years. In collaboration with industry, governments around the world are investing large sums in multi-year programs to facilitate commercial development. Through acquisitions, joint ventures, and licensing agreements, the firms involved have become increasingly multi-national and are able to obtain access to growing markets and achieve lower production costs. Critical technological advances continue to be made outside the United States, for example, carbon fiber technology developed in the UK and Japan and hot isostatic pressing technology developed in Sweden.

This trend toward internationalization of advanced structural materials technologies has many important consequences for government and industry policy makers in the United States. They can no longer assume that the United States will dominate the technologies and the resultant applications. According to a National Research Council Report, the United States is already lagging behind other nations in applying advanced materials to manufacturing processes.

The technology flow into the United States may soon be just as significant as that flowing out. Moreover, the increasingly multi-national character of material industries suggests that the rate of technology flow among firms and countries is likely to increase. The United States will not be able to rely on a superior R&D capability to provide an advantage in developing commercial products. Furthermore, if there is no existing infrastructure in the United States for quickly appropriating the R&D results for economic development, the results will quickly be used elsewhere.

2. Exchange Agreements

There is a high level of exchange activity in the area of high-strength composites, in both basic materials and a wide range of applications. NATO programs for physics and electronics provide a mechanism for exchange of scientific information regarding the basic physics of structural material. Defense Advanced Research Projects Agency (DARPA) memorandums of understanding (MOUs) specifically cover the use of composites in armor and anti-armor.

The Technology Cooperation Program (TTCP) provides a vehicle for a range of applicable exchange activities relating to basic material, ceramics, non-destructive evaluation, and materials performance.

Each of the Services also has exchanges, primarily with NATO and with friendly nations in areas of specific interest. These include exchanges of technology in such diverse areas as structures and materials for combat aircraft and basic studies in fatigue properties of aircraft structures and dynamic behavior of materials under stress.

19. SUPERCONDUCTIVITY

19. SUPERCONDUCTIVITY

A. DESCRIPTION OF TECHNOLOGY

Conventional electrical, electronic, and electromagnetic devices and systems (e.g., power lines, computers, and electric motors and generators) suffer performance limitations and undesirable power losses as a consequence of the electrical resistance inherent in normally conductive materials. This technology makes use of the zero resistance property andother unique and remarkable properties of superconductors for creation of high-performance sensors, electronic devices and subsystems, and supermagnetbased systems. Introduction of superconducting devices offers the potential for reducing drastically the energy lossesand cooling requirements, which in turn makes for much improved processing speed andpackaging density in digital microcircuitry. The frequency selectivity in analog filters using superconductor elements can not be approximated by other types of devices. The recently discovered high-temperature superconducting materials offer further decreasesin cooling requirements, promising the use of liquid nitrogen, rather than helium as acollant, which makes potential applications much more practical.

Superconductivity technology of current interest encompasses low-temperature superconductors (LTS) (transition temperature less than 23K) and the new oxide high-temperature superconductors (HTS) (transition temperatures as high as 125K or more). The most commonly used LTS material is a very ductile alloy of niobium and titanium, which is corrosion resistant, is easily formed into supermagnets, and exhibits moderately high superconducting performance. Brittle metallic LTS materials (e.g., Nb_3 Sn) also offer higher performance (higher current density at higher magnetic fields at higher temperatures) but are difficult to fabricate because of their brittleness. The LTS materials niobium and niobium nitride are commonly used in superconducting sensor and electronics applications. With these materials, large arrays of Josephson junctions are readily fabricated.

HTS materials offer much higher operating temperatures and much higher operating magnetic fields than their LTS counterparts, and they appear to possess potential for supporting electric current densities adequate for many applications. However, most HTS materials also possess highly anistropic properties, are very brittle, and are highly susceptible to moisture. And HTS end products, whether supermagnets, electronic devices, sensors, or passive magnetic bearings, are more difficult to fabricate than their LTS counterparts.

DoD superconductivity R&D extends from searches for theoretical understanding, to materials characterization, materials processing, invention and architecture, and finally engineering test models and operational systems that involve superconductivity. Of concern are issues related to the basic properties of superconductors, their manufacture and fabrication into usable configurations, and their unique device and systems applications. These applications capitalize on the abilities of superconducting to support loss-less DC currents and low-loss ac currents, levitate, shield magnetic and electromagnetic fields, sense magnetic and electromagnetic fields with unmatched sensitivity, transmit electronic signals with extremely little distortion, and fulfill analog and digital electronics functions at speeds 10 to 20 times faster and at power dissipation 1,000 times less than is currently possible with semiconductors. Critical to all such applications are efficient and reliable refrigeration systems.

Defense-related research and development plans in this critical technology area focus on low temperature superconductors and on high temperature superconductors, which comprise the two major technology sets which provide key inputs to achieving the potential of this technology. LTS supermagnet-based technology addresses ship propulsion, power systems, and magnetic launchers. Corresponding HTS supermagnet activity focuses onmore elementary aspects, viz., materials, conductor processing, and primitive magnets. Sensors and electronics efforts in both LTS and HTS materials are concerned with passive devices, detectors, Josephson Junction-based and weak link-based active devices, and digital logic and memory.

Technology Sets in Superconductivity

- Low temperature superconductors
  - Supermagnetics
  - Sensors and Electronics
- High temperature superconductors
  - Supermagnetics
  - Sensors and Electronics

Large-scale LTS technology has progressed to the point where thousands of supermagnets are now in routine use around the world in magnetic resonance imagers and in high-energy particle accelerators. The first steps have also been taken for the application of LTS to military systems such as compact and efficient electric drive systems for ships. LTS sensors and analog electronics devices have also been highly developed. However, LTS digital electronic systems are at an earlier stage of development, and the United States trails Japan in this high-risk, high-potential-payoff technology. Overall, LTS technology promises high utility not only in its own right, but also in modeling systems to be later executed in HTS materials when feasible.

HTS materials are in an earlier stage of development. Because HTS materials are difficult to process, a heavy and sustained investment in R&D will be required if their apparent potential is to be realized. Production of high-quality films and development of patterning techniques are high-priority goals, as are high-current-density bulk HTS materials suitable for power transmission, supermagnets, bearings, motors, and generators. The course of HTS development will probably proceed from passive analog electronic components, to electromagnetic sensors, digital electronics, small supermagnets, and finally large-scale supermagnet applications.

B. PAYOFF

1. Impact on Future Weapon Systems

Potential superconductivity applications, many of which have already been tested in LTS prototype form, include more compact, higher efficiency electric drive systems for ships and submarines (and possibly land vehicles and aircraft), electric generators, electric energy storage systems for directed energy weapons, superconducting cavity particle accelerator directed energy weapons, electromagnetic guns and aircraft catapults, magnetic and electromagnetic shields, supermagnets and cavity resonators for microwave and millimeter-wave generation. Further applications involve: magnetic and electromagnetic sensors (DC through infrared); infrared focal plane arrays; superconducting quantum interference devices (SQUID); magnetic gradiometers and magnetometers; high-power sonar sources; ultra-high-speed, ultra-compact signal processors and computers; low-loss narrow bandwidth filters; compact low-loss delay lines; high-performance low-noise communications and surveillance systems; superconducting antennas; and superconducting gyroscopes, inertial sensors, gravimeters and magnetic mine detectors. Many of these systems are unique, having no normal conductor counterparts (e.g., superconducting magnetic energy storage systems and SQUID sensors). The development of such SQUID sensors will provide new magnetic anomaly detection (MAD) methods for finding acoustically quiet submarines. In the long term (10 years or more) the potential exists for new capabilities to be brought to platforms incapable of supporting conventional semiconductor counterparts because of size, weight, or power requirements. For example, with superconducting electronics technology, placing ultra-high-speed supercomputer capabilities on board aircraft and spacecraft should be feasible; this capability currently is not feasible with semiconductor technology because of its large input power requirements (200 kilowatts) and associated massive cooling system requirements.

In all cases, the performance advantages of such systems must be adequate to more than compensate for the necessary refrigeration requirements.

2. Potential Benefits to industrial base

DoD efforts in superconductivity offer substantial potential for beneficial effect on the industrial base. The development of compact, efficient motors and generators as well as low-loss cables for power transmission and energy storage devices will lead to improved distribution and utilization of electrical energy. Such future systems may offer greater immunity from brown-out, be more easily repairable (due to small size), and, where necessary, allow local control of available energy to improve industrial production. Magnetic resonance imaging, a billion-dollar-per-year industry, will become more accessible for routine use, thereby minimizing invasive diagnostic surgery. Progress in superconducting electronics may ultimately lead to higher performance supercomputers and mainframe computers. Advanced, very stable oscillators will permit increases in communications spectral density. Magnetic sensors based on SQUID technology will be used for medical monitoring and diagnosis of brain function.

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

Defense-related development plans are centered upon key issues in both LTS and HTS materials and devices. The following describes the key objectives and major milestones in this critical technology.

a. Low Temperature Superconductors (LTS)

The long term objectives for this technology set are: (1) widespread military utilization of Niobium-based analog and digital electronics systems for ultrafast, real-time sensing and signal processing on military platforms on land and sea, and in air and space; and (2) the routine use of low temperature superconductor magnets in a variety of propulsion and energy storage applications.

Development efforts in the area of electronics and signal processing will include the development of components for LTS digital logic, memory and sensor components, and the implementation of single flux quantum (SFQ) logic and analog signal processors. Among the anticipated milestones:

- 1991
  - LTS analog to digital converter
  - LTS infrared sensor
- 1992

- 100 GHz SFQ logic circuit
- SFQ Analog signal processor

- 1993
  - 1 GHz digital signal processor
  - 1K LTS cache memory
  - Infrared sensor array
- 1994
  - 400 GHz SFQ logic circuit
  - Prototype MAD ASW system
  - Analog receiver front end
- 1995
  - 1024 x 1024 digital cross bar switch
  - 4K LTS cache memory
- 1996
  - SFQ signal processor
  - Analog communications and surveillance receivers
- 1997
  - LTS Nb/NbN chip level technology
  - Infrared focal plane array with processor.

Systems developments in the area of supermagnets include LTS-based ship drive systems, magnetohydrodynamic ship propulsion systems, magnetic launchers, and LTS magnetic energy storage for directed energy weapons power supply. Anticipated milestones include:

- 1991
  - Rotating electrical machinery available for scale up for ship drive
  - Engineering design of 72 GigaJoule magnetic storage DEW power supply
- 1993
  - MHD propulsion system sea-going test vehicle design
  - Complete design of magnetic launcher demonstrator
- 1996
  - Complete construction of MHD ship propulsion test vehicle
  - Complete construction of magnetic launch demonstrator

b. High Temperature Superconductors (HTS)

The long-term objectives for this technology area are: (1) the achievement of complete communications and surveillance receivers using low radio-frequency-loss film passive electronics technology; (2) the development of HTS weak link and Josephson Junction (JJ) electronics technology as the basis for a variety of advanced sensors and electronic processors; and (3) the development of HTS supermagnets for new applications and retrofit of LTS supermagnets. Among the anticipated milestones:

- 1991
  - — Analog components for HTS passive electronics technology
  - — weak link–based magnetic sensors
  - — Supermagnet conductor material, 10^3 A/Cm^2 at 3T, and 50 degrees K.
- 1993
  - — HTS interconnects on semiconductor chips and multi–chip modules
  - — weak link–based and/or JJ–based infrared sensors
  - — Supermagnet conductor material, 10^4 A/Cm^2 at 3T, and 50 degrees K.
- 1995
  - — Analog signal processor for HTS passive electronics circuits
  - — Modest complexity weak link and/or JJ arrays
  - — Supermagnet conductor material, 10^4 A/Cm^2 at 5T, and 60 degrees K.
- 1996
  - — Capability to produce moderate lengths of supermagnet conductor material
  - — Liter–sized low performance HTS supermagnet
- 1997
  - — HTS passive electronics receiver front end
  - — JJ–based analog to digital converters

2. Technology Objectives

Technology Objectives — Superconductivity

Technical Area	By 1996	By 2001	BY 2006
Materials and processing	• Higher transition temperature HTS materials • Quality HTS tunnel junction arrays • Higher critical current densities in ceramic materials • Long HTS wires; prototype conductors • Large-area HTS films for shielding and cavity resonators	• Higher transition temperature HTS materials • Quality HTS tunnel junctions in large arrays • HTS conductors suitable for supermagnets • Theoretical undersanding of HTS	• Codified manufacturing processes for materials production and fabrication
Sensors	• LTS IR focal plane arrays • HTS sensors, DC to IR • LTS inertial and gyro sensors	• LTS MAD ASW systems • HTS IR focal plane arrays • HTS inertial and gyro sensors	• Widespread use in a variety of sensor platforms
Superconducting electronics	• LTS analog communications and surveillance systems • HTS analog communications and surveillance components • HTS A/D converters • LTS Nb/NbN digital chip-level technology • HTS interconnects for semiconductor circuits • HTS digital electronics array technology	• HTS analog communications and surveillance systems • LTS Nb/NbN digital signal processor and memory • HTS digital chip-level technology • HTS satellite system	• Widespread use of superconducting electronics
Supermagnetic-based applications	• Prototype LTS magnetic gun • Test of LTS MHD ship propulsion systems • Modest-performance HTS supermagnets	• Engineering of operational LTS rotating electrical machines • Engineering of operational LTS magnetic energy storage system • Engineering of operational magnetic gun • Engineering of operational MHD ship propulsion system • High-performance HTS supermagnets	• Widespread use of superconducting magnets in industry, academia, and defense
Particle accelerators	• Low-loss HTS cavity resonators	• Prototype HTS cavity resonator particle accelerator	• Widespread use in academia and defense research

3. Resources

A summary of S&T funding[18] for superconductivity technology is given in the following table.

Funding — Superconductivity ($M)

FY87–91	FY92	FY93	FY94	FY95	FY96	FY97
345	56	51	54	54	55	57

4. Using the Technology (Examples)

a. Magnetic Sensors Using Superconducting Quantum Interference Devices

The objective of this project is to field test two advanced-design superconducting gradiometer prototype systems. The first will be of all-thin-film design and operate at liquid helium temperatures with a 40 dB improvement in performance over the current system. The second device will operate at liquid nitrogen or neon temperatures with a 20 dB performance improvement over the current system.

Three paths are being explored to develop an advanced superconducting gradiometer. This approach provides ample time to develop technology options to select the most promising approaches and to reduce risk. The first is an LTS effort to develop an advanced-design thin-film, single-axis gradiometer to be used in environmental noise characterization; the second allows for the development of a five-axis LTS gradiometer and demonstration field testing; the third pursues the development of an HTS gradiometer with demonstration field testing.

During the first phase of the LTS single-axis development, advanced designs and system noise sources are studied and materials are characterized. This leads to selection of materials, fabrication technology, and device designs. In the next phase, these selected approaches are then fabricated and evaluated in an iterative process in order to refine techniques and produce optimal devices. Resulting devices are then integrated into a specially configured test dewar, and performance is demonstrated and characterized.

b. Power Applications of Superconductivity

The goal of this program is to develop a high-power superconducting integrated power system for shipboard use. DoD is developing superconducting ship propulsion systems. A 3,000-horsepower LTS superconducting propulsion system has been demonstrated at sea. Critical-risk reduction issues must now be addressed to ensure the eventual fleet implementation of this technology. The combat environment places stringent requirements for resistance to shock, vibration, and mechanical stress, which other power applications programs do not address. The major critical-risk reduction issues for this technology are the development of an efficient and reliable refrigeration system for a shock and vibration environment and the development of a more stable superconducting wire and magnet system.

DoD is also conducting an exploratory development project for selective power applications of superconductivity using LTS technology. The work will complement the

[18]Funding shown above for FY1992 and subsequent years is highly speculative, in part because of the uncertainty in the time scale within which various applications are likely to become feasible, and in part because many projects involving superconductivity involve other technologies as well, and so the portion of the funding allocable to each technology is often debatable. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

planned advanced electric drive program and will focus on those critical-risk issues that need further exploratory development. These issues include: development of advanced and more stable conductors (Al/NbTi and Cu/NbSn), which will significantly reduce the risk of suddenly losing superconducting performance or alternatively reduce the overall size and weight of rotating electrical machines; systematic study of magnet instabilities and their relation to conductor and magnet design; and development of turbine expander and Gifford-McMann refrigeration systems for improved reliability. Assessments of the effects of HTS materials will be made continuously; however, at the present time, superconductivity motor applications of HTS seem far term because many materials problems must be overcome.

DoD has been successful in demonstrating lightweight, efficient power generation components using LTS materials and technology. Extensive knowledge and experience gained in this LTS application will provide a foundation for eventual introduction of high performance, efficient power generation, and power distribution components with HTS materials.

c. Space Applications of High-Temperature Superconductivity

The objective of this project is to demonstrate the feasibility of incorporating the revolutionary technology of high-temperature superconductivity into space systems. The unique properties that superconductors exhibit can provide space surveillance, communications, navigation, weather, and weapon systems with performance capabilities far superior to those possible using conventional technologies. Superconducting technology can provide advances in spacecraft performance such as improved signal isolation with high-Q filters, dispersionless delay and transmission lines, detectors with multispectral sensitivity (from microwave to infrared), infrared focal plane electronics, and traveling wave tubes (TWTs). Superconductors also offer quantum-limited detection (that is, as sensitive a detector as is theoretically possible).

The cryogenic equipment required for the operation of LTS materials limits the extent of their use in the space environment. However, HTS materials, with operating temperatures above 80K, can utilize simple radiative cooling in space and hence make the use of superconductivity on spacecraft convenient for the first time.

Because HTS technology is so new, experimental data for modeling and making projections are limited. Space experiments are being carried out to reduce the development risk before considering HTS applications in operational space systems. The results of the space experiment will enable operational systems designers to evaluate both the benefits and possible problems of using superconducting components in their systems. The initial launch opportunity for the space experiments is FY1991, but a FY1992 launch is more likely.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

Today's "superconductivity industry" can be roughly divided into two segments: one comprising firms that produce products based on Low Temperature Superconductor (LTS) applications, the other based on High Temperature Superconductor (HTS) applications. The highly developed LTS-based industry provides commercial products and serviceswire and cable, magnet winding, analog electronics, and sensors, while the HTS-based industry, new and not as far advanced, largely provides information, "knowhow," and special devices for laboratory applications. At this time, the HTS industry is attempting to develop the materials for future applications of electronic components, medical and industrial instruments, and eventually electric power and transportation equipment subsystems. It is not uncommon for firms to be involved in R&D, and sometimes production, for both low- and high-temperature components for defense and commercial applications.

Although the HTS and LTS industries are currently somewhat distinct, the two industries will doubtless achieve greater coalescence as HTS matures and begins to compete for applications served by LTS and non-superconducting material technologies. There are important reasons for better integrating the two segments, and experts believe that this merger will be necessary for the industry as a whole to become highly profitable. For example, revenues generated from the sale of near-term LTS-based products could be used to underwrite needed research for longer-term HTS applications. The two technologies already share some common infrastructure and it is anticipated that additional industries will develop to help HTS and LTS firms resolve product and manufacturing process difficulties that affect both technologies.

High-temperature superconductors are currently being produced in two forms: films (deposited on substrates) and bulk materials. Films of very high quality and performance have been achieved and are suitable for electronic and microwave applications. Bulk HTS are currently fabricated using a variety of techniques, including multi-textured growth. Highest current density is achieved by controlling crystal size and orientation. However, to date the performance characteristics achieved with bulk HTS materials are relatively modest, and very substantial improvements will be required before their widespread utilization can be realized.

2. Projected Industrial Capabilities

Bulk HTS materials are required in wire form for electromagnets; however, the brittle nature of HTS materials imposes limitations. Either use is restricted to magnets of very little curvature or, alternatively, techniques must be developed for fabricating electromagnets by forming them from compressed powders first and then firing them to final ceramic form.

For both bulk and thin-film HTS materials many fabrication obstacles must be overcome for them to be useful in their planned applications. The properties, particularly the superconducting properties, must be reproducible. Currently, these fabrication processes are performed on the research level and are not as reproducible as desired. Also, some HTS materials contain hazardous or toxic elements (such as thallium). The safe fabrication, use, and storage of these materials must be addressed and solved. Stability of materials is also a concern. Some of the elements used in these HTS compounds are moisture sensitive. Specific environmental conditions must exist during fabrication, storage, and use of these materials, and suitable protective coatings must be developed.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

With federal funding, aspects of superconductivity R&D are being pursued in U.S. universities, industry, and government laboratories. Federal support is centered primarily in DoD, DoE, NASA, the National Science Foundation (NSF), and the Department of Commerce (DoC).

DoD supermagnet-based applications may be expected to benefit significantly from the extensive DoE efforts on supermagnets. However, DoD interests in superconducting sensors, analog electronics, and digital electronics are being addressed at only very modest levels in other agencies and industry. Thus the U.S. competitive position in these important areas appears to be highly reliant on the success of DoD efforts.

NSF supports fundamental research on theories and properties of superconducting materials. Fundamental research also includes efforts to synthesize new superconducting materials and to understand how these materials can be processed into useful forms. Current efforts are part of ongoing programs for materials research, chemistry, physics, and engineering. NSF also provides funding for the Center for High Temperature Superconductivity which focuses research on synthesis, bulk properties, theory, thin films, microstructural characterization, and ceramic processing. Ninety percent of NSF support goes to research on high temperature superconductivity.

Of course, all DoD superconductivity activities will benefit significantly from NSF-sponsored investigation of the basic and fundamental nature of superconductivity and from NIST research programs. NIST goals are, first, to establish measurement techniques, standards, and data to support engineering with superconductors and, second, to develop superconducting electronics, primarily for measurement techniques, instrumentation, and physical standards.

2. R&D in the Private Sector

In the United States, the private sector provides about half the amount of funding for superconductivity R&D as that provided by the federal government. A few large companies (in the communications, computers, and chemicals industries) are most active, and they depend only little, if at all, on federal funds for their superconducting activities. More modest privately funded superconductivity R&D efforts are underway in other companies, usually to augment federally supported activities. These companies include large defense, aerospace, electrical, and electronic companies; well-established small companies that market superconducting wire, magnets, and instruments; and small venturecapital firms that have recently been established in attempts to capitalize on the recent advances in high-temperature superconductivity. Together these private-sector-funded activities are of great benefit to the overall national capability in superconductivity R&D.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

The table on the following page provides a summary comparison of United States and other nations for selected key aspects of the technology. Ongoing international research and development indicates potential international capabilities to contribute to United States challenges and goals including:

- Fundamentals, synthesis, and increased transition temperature of HTS
- Development of material processing and fabrication techniques for HTS applications
- Electronics applications and integration of superconducting elements with semiconductors
- Power applications.

Overall, Japan and the United States share a worldwide lead in this technology and are on a par, but Japan has a significant lead in digital superconducting devices and systems. Unlike the United States, where Josephson junction (JJ) digital electronics research was all but terminated in the early 1980s, Japan has continued research effort in this area. Moreover, they have developed niobium technology to a high level of sophistication, and have overcome the long-term stability problems of the lower melting point metals which accounted in part for the abandonment of this technology by US industry. Supported by Ministry of International Trade and Industry (MITI) programs, Japan has continued to develop LTS digital logic and memory assemblies for computing applications. Component densities (20,000–30,000 JJ chips with digital logic and 4K memories), while low, have been steadily increasing. Japan's organization and industrial emphasis is on materials processing as a key enabling technology for all applications. Japanese industrial research is notable for the number of companies conducting vigorous, internally funded, high-quality efforts, suggesting a potential for rapid adoption of HTS products in Japan. In the long term, this emphasis may position Japanese industry for a sustained lead in this area.

While Japan and the United States are expected to remain the leaders in superconductivity, many other countries are active in the field, and NATO has very significant capabilities. Europe has traditionally been strong in basic research, but has trailed in applications with the exception of areas such as magnets and cables. Companies in the UK and Germany are leading producers of magnets for medical imaging. In addition, the CERN supercollider project is providing impetus to these areas of research.

Virtually all European nations (most notably the UK, Italy, and Germany) have national programs in HTS involving both government and industry. For example, the UK Atomic Energy Authority has established a collective search for new superconducting materials. This program is patterned after a successful program addressing electronic ceramics in the early 1980s and will involve standardized automated testing of materials. As yet, clear patterns of international cooperation at the governmental levels (comparable to the Joint European Submicron Silicon Program or the European Strategic Program for Research in Information Technology) have not emerged. At the research activity level, however, international ties are being forged, offering the promise of a better integrated and fruitful NATO effort in the future.

Soviet research in thin film SQUIDs is considered to be comparable to Western research in this area. The Institute of Radioengineering and Electronics, Moscow (Soviet Academy of Sciences) has developed a SQUID with a sensitivity of 5 x 10-31 and noise of 5 x 10-32 Joule/Hz. Performance is comparable to devices made at Lawrence Berkeley Laboratory and IBM and somewhat better than those commercially available in the United States. The Department of Physics at Moscow State University has been active in constructing SQUID sensors for at least the last five years, producing both rf and dc SQUIDs operating at the 10^{-31} Joule/Hz level. The primary application is intended to be in digital processing. The Novosibirsk Electrotechnical Institute is promoting its rf and dc SQUIDs as being comparable to the best commercially available devices. System bandwidth is claimed to be greater than 30 kHz; control of up to 16 channels also is claimed. The Institute is interested in cooperative programs.

Eastern European nations are also conducting research in SQUID technology. The Physics Institute at the Czechoslovakian Academy of Sciences, Prague, constructed a 400 MHz rf SQUID with a sensitivity of 2.6×10^{-29} Joule/Hz. The Slovak Academy of Sciences has advertised a laboratory rf SQUID system for sale that is comparable to commercially available rf SQUID systems. The Institute of Physics in Prague, Czechoslovakia, incorporated SQUIDs into a susceptometer and built a three-axis geophysical magnetometer with a sensitivity better than 100 fT/Hz. At the Slovak Academy of Sciences, Bratislava, the Institute of Electrical Engineering, Electro-Physical Research Center, is known to be conducting theoretical, experimental, and applied research on the Josephson effect and superconducting electronics.

Summary Comparison — Superconductivity

Selected Elements	USSR	NATO Allies	Japan	Others
Fundamentals, synthesis, and increase of transition temperature of HTS	□□	□□	□□□ ○	□□ China, Switzerland □ India, Israel
Develop material processing and fabrication techniques for HTS applications	□□□ –	□□	□□□□ +	□□ China, Switzerland □ India, Israel
Electronics applications and integration of superconducting elements with semiconductors	□	□□	□□□ ○	□ China, India, Israel
Power applications	□□□ ○	□□	□□□ ○	□ China, India, Israel
Overall[a]	□□	□□	□□□□ ○	See above for niche capabilities

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□	broad technical achievement; allies capable of major contributions
□□□	moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
□□	generally lagging; allies may be capable of contributing in selected areas
□	lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

+	Foreign capability increasing at a faster rate than the United States
○	Foreign capability increasing at a similar rate to the United States
–	Foreign capability increasing at a slower rate than the United States

2. Exchange Agreements

DoD-sponsored exchange activity in the area of superconductivity has been modest, but significant. The NATO program in physics and electronics has provided a mechanism for exchanges of fundamental scientific information. The Technology Cooperation Program (TTCP) groups in basic materials and electronics materials provide several potential mechanisms for cooperative exchanges in fundamental science, and some limited exchange of information may occur for specific applications of the technology to instrumentation and military electronics.

20. BIOTECHNOLOGY

20. BIOTECHNOLOGY

A. DESCRIPTION OF TECHNOLOGY

Owing to the discovery and exploitation of genetic mechanisms that control living organisms, it is now possible to engineer microbial, plant, and animal cells to act as factories for the synthesis of existent or new materials at substantially enhanced rates and efficiencies. These same techniques make it possible to unravel Nature's secrets for fabricating structural materials and exquisite sensors capable of detecting single molecules or a single photon in low signal-to-noise environments. Biosynthesis of new enzymes, which are biological catalysts, offers the prospect of developing new pathways for synthesis or degradation of chemicals. Application of these techniques comprise the field of *non-medical biotechnology* and DoD has become an international leader in this critical technology.

Technology Sets in Biotechnology

- Processes
- Materials
- Sensors

B. PAYOFF

1. Impact on Future Weapon Systems

DoD is constantly pressing the forefront of materials technology both because of the severe work environments and the need for extremely high reliability. Biotechnology offers an attractive means for producing new classes of materials, at low cost, with the added strategic advantage of using non-petroleum-based feedstocks. The cost of development of new materials is also likely to decrease when they are produced biotechnologically because of the potential for producing "generic" materials that may be easily modified at the molecular level without the need to develop a new manufacturing scheme. The time of transition for a biotechnologically produced material from demonstration of principle to product is estimated to be 3 to 4 years, which is about one-third the time required for development of conventional materials.

Requirements for sophisticated sensors are increasing dramatically for: assessing airborne and submarine threats; monitoring the environment for toxic wastes; determining organisms responsible for fouling or corrosion; and monitoring treaty compliance. Biologically-based sensing devices provide unique capabilities for selectivity and sensitivity. In an era of peace the demand for new, expanded sensor capabilities will increase faster than the demand for new weapons systems because of the greater need to detect and monitor unfriendly activity.

DoD's significant hazardous waste problem and the enormous cost of the required clean-up (remediation) of DoD sites has received recent public attention. This cost cannot be deferred because compliance is a legal requirement, and use of conventional methods could significantly affect DoD operational resources. Biotechnology offers a viable, cost-effective alternative for the permanent solution of many of the DoD hazardous waste problems by using microbial or catalytic methods to degrade wastes and explosives, and to synthesize biodegradable plastics and anti-fouling paints. Biodegradation technology also provides approaches to improved maintenance methods, such as plastics, paint, and scale removal.

Thousands of contaminated sites will require billions of dollars to clean up using conventional treatment methods such as removal, followed by incineration or landfill burial and pump and treat systems using physical/chemical treatment methods for groundwater. Biodegradation, either in above-ground reactors or in situ, offers an extremely effective, destructive method to deal with the overall site remediation problem. Advances in the scientific understanding of the biodegradation process will also have a major payoff for treating a multitude of DoD waste streams. Since waste stream treatment and disposal are directly related to life cycle cost, technical advances can be expected to reduce the ever-increasing costs of current and future defense systems.

Some specific goals and payoffs anticipated from the DoD materials biotechnology initiative are given in the table on the following page.

2. Potential Benefits to the Industrial Base

The ability of certain organisms, or enzymes derived from these organisms, to perform specific chemical transformations under a wide range of conditions can be turned to useful advantage to produce products with unique applications or to solve hazardous waste and metal extraction problems. Bioprocesses have the intrinsic advantage of requiring far less energy and therefore can be considerably less costly. They are also less environmentally damaging and proceed with greater speed, specificity, and selectivity than do conventional processes. Additionally, recombinant DNA technology can be used to tailor organisms to perform specific tasks or to manufacture products that would be difficult or costly to obtain using conventional methods.

Biotechnology offers numerous dual-use applications. In particular, DoD investment in the biomaterials R&D area has already begun to produce products that benefit the industrial base. Examples are bioengineered silk fibers which provide high strength, lightweight materials and improved ballistic performance. Another important example is an array of biosensors used as a chemical detection and monitoring device. Microorganisms developed for DoD paintstripping have shown potential for removal of paint from aluminum cans prior to recycling.

Specific Goals and Payoffs — Biotechnology

Goals	Payoffs
Biosensors	
• Receptor-based sensors	• Identification of organisms
• Immuno sensors	• Improved real-time detection and identification of chemicals, pathogens, toxins, explosives, and drugs
• Nucleic-acid based biosensors	• Improved non-acoustic undersea surveillance
• Optical-based microsensors	• Detection of pollutants at low levels
• Molecular channels	
Bioprocesses	
• Biological crystal growth	• Tailored inorganic crystal sizes and shapes for ceramics and electronics
• Waste site bioremediation	• Low-cost, permanent solution for persistent toxic substances
• Bio-paintstripping	• Elimination of hazardous solvents for removal of paint from aircraft
• Enzyme decontamination and surfactants	• Selective decontamination and cleaning agents
• Synthesis of energetic compounds	• Lower cost and improved safety for high-energy materials
• Bio-degradation of energetic compounds	• Low-cost, environmentally safe disposal
Biomaterials	
• Understanding natural designs, enzymes, and pigments	• Optical integration of sensing, decisionmaking, functional capability, and mechanical properties in "smart" structures
• Recombinant-derived fibers	• Improved light-weight, high-strength materials
• Biosynthetic polymers	• Low-cost, low-weight, high-strength organic matrix composites for aircraft
• Catalytic polymers	• Self-decontaminating materials for individual and collective protection
• Bioelastomers	• Seals, gaskets, coatings with better chemical and mechanical properties
• New antifoulants	• Environmentally safe coatings for ships, buildings, and bulkheads with improved performance
• Bioadhesives	• Low-cost, high-performance lubricants
• Biosynthesized lubricants	• Improved manufacturing and processing of ceramic composites and powders
• Bioceramics	• Photoresponsive materials and coatings for signature reduction
• Immobilized protein-pigment complexes	• Improved ballistic and camouflage protection
• Self-assembling protein arrays	• Laser protection
• Biomolecules with nonlinear optical properties	• Light-based computers
	• Low-cost microcircuit manufacturing
• Thin-film, self-assembling molecular arrays	• Increased circuit density and speed with decreased size; three-dimensional logic capability
• Improved metallized biotubule fabrication	• High-power microwave and energy storage devices

C. S&T PROGRAMS

1. Summary Description of Plan for Technology Development

a. Processes

(1) Objectives

The basic goal of this effort is to discover and apply nature's strategies for coping with undesirable chemicals or organisms. Selected applications include: decontamination of chemical warfare agents; biodegradation of hazardous waste products; waste reduction in painting and paint stripping; and development of environmentally sound approaches for prevention of biodeterioration (fouling and corrosion) of surfaces exposed to marine environments.

(2) Development Milestones

Basic research efforts in decontamination technology are aimed at developing generic approaches to design of enzymes for catalytic degradation of broad classes of chemical warfare agents. There is a great need to be able to develop enzymes rapidly and inexpensively that will exhibit high activity for new chemical agents. FY 1995 is the target for meeting this goal. Testing of protective coatings and camouflage creams using existing enzymes is expected to be completed by FY 1993. This effort has been accelerated significantly during 1990 to meet the demands of Desert Shield/Desert Storm and a number of new materials will be produced in FY 1991. This is an instance where technological readiness has served U.S. interests well.

Bio-paintstripping research is directed along two independent lines: one to prepare a paint that can be metabolized by specific organisms that do not exist naturally and; second, to identify or engineer organisms capable of metabolizing existing paints. The objective in both instances is to reduce the amount of organic solvents used to apply and remove paints and to decrease the amount of toxic substances (including heavy metal ions produced from metal lost in the surface abrasion) released to the environment. Milestones include: identification of candidate organisms by FY 1994; biodegradable coatings development by FY 1996; and engineering of organisms for target paints by FY 1998.

An area of increasing concern to DoD is that of hazardous waste decontamination. When decontamination is accomplished by biological means (using either organisms or extraorganismal enzymes in solution) it is referred to as bioremediation. Funding in this area is expected to increase steadily over the next several years because biological approaches appear to be the most cost-effective in reducing concentrations of toxic materials to acceptable levels. Milestones for these efforts include: development of probes for identification of naturally-occurring organisms present at waste sites by FY 1993; identification of key organismal traits conveying "robustness" or survivability in the presence of high concentrations of toxic wastes by FY 1995; and delineation of important consortial (multi-organismic) processes responsible for complete degradation or detoxification of toxic materials by FY 1998.

Most living creatures in the sea make their living attached to surfaces as "fouling" organisms. Consequently, many large plants and animals have had to develop strategies to avoid fouling. Such strategies include constant shedding of surfaces (e.g., most fish) and production of *antifouling agents* (e.g., corals and seagrasses). This technology will rely upon identification of antifouling agents expected to be complete by FY 1994 and development of new coating technology that will permit slow and steady release of such agents by FY 1997. The new coating technology is expected to rely upon biological products and strategies and so falls within the realm of biotechnology, as does the identification and biosynthesis of the antifouling agents.

b. Materials

(1) Objectives

Biological systems offer many examples of structural materials that exhibit properties that exceed those available using conventional materials technology. Moreover, biotechnologically-produced materials are inexpensive, strategically relevant because they need not rely upon petroleum feedstocks, and their structures can be manipulated at the molecular level without developing new processes. The ultimate goal of DoD biotechnology materials programs is to develop generic materials with a range of properties that can be selected for specific applications or uses. A second objective is production of fine chemical intermediates that cannot be produced economically in quantity by conventional chemistries. DoD has research programs aimed at the following classes of materials: fibers, coatings, adhesives, plastics, elastomers, lubricants, composites, and electro-optical materials.

(2) Development Milestones

Both Navy and Army have research programs directed at synthesis of modified forms of natural fibers with an emphasis on *spider silk fibers*. These fibers are stronger than steel on a weight basis and have the extensibility of natural wools. Applications areas include protective clothing, armor, biodegradable parachutes, undersea tow ropes, and missile control lines. Milestones are cloning and expression of silk genes by FY 1993, modified silks produced in quantity by FY 1996, and scale-up tests complete by FY 1998.

Biosynthesis of *plastics* is a DoD objective for four reasons: to gain a strategic advantage by avoiding dependence on petroleum feedstocks; to prepare plastics that cannot be made by conventional polymer chemistry; to lower the cost of materials used in large quantity; and to prepare biodegradable materials for disposable items. DoD funds the majority of federally-supported research on biodegradable plastics. Currently both basic research on polyesters and applied research using starch and other carbohydrates for disposable plastic bags are supported. Milestones include: tests of disposable plastic bags in FY 1992; development of measures of biodegradability in all DoD operating environments by FY 1994; demonstration of plastic synthesis in plants by FY 1996; and demonstration of large-scale biosynthesis technology for thermoplastics by FY 1998.

Exploration of marine mussel *adhesives* is aimed at clarifying fundamental processes in adhesion, with an emphasis on adhesion in moist environments, and has an ultimate goal of preparing a generic adhesive whose properties can be tailored for the environment and bonding surface. The gene for several mussel adhesives has now been sequenced and cloned and commercial production of mussel-like adhesives began in FY 1991. DoD-sponsored research has disclosed that natural marine adhesi[illegible] are foam composites; this observation and its practical implications are under investiga[illegible]. The goal of a generic adhesive now appears to be achievable by FY 1994.

c. Sensors

(1) Objectives

Sensor technology plays a critical role in a wide range of DoD activities. Several of the most highly developed application areas are chemical or biological warfare defense, threat detection at sea (e.g., antisubmarine warfare) and on land (e.g., explosive sniffers), drug interdiction, contaminant assessment, and identification of biodeterioration organisms.

Biological sensors can have extremely high selectivity and sensitivity exceeding anything obtainable by non-biological sensors. The objective of the DoD sensor effort is to discover the basic principles used by living-system sensors and exploit them in designing new sensors.

(2) Development Milestones

Chemical and biological warfare defense (CBWD) requires state-of-the-art detection schemes to provide real-time threat assessment. *CBWD detectors* currently depend upon one of several types of biotechnology: antibodies, receptors, enzyme reactions, and DNA/RNA probes. These technologies have been and continue to be developed almost exclusively under DoD sponsorship. First-generation, antibody-based detectors are nearing completion and will be field-tested during FY 1991; second-generation detection schemes are in the basic research stage and will be demonstrated in FY 1993. Detection schemes based on enzymatic reaction schemes will reach commercial production in FY 1991 because of the acceleration of these efforts caused by Desert Shield-Desert Storm. Probe technologies which focus on biological agents are expected to receive rapid development during FY 1991-1992. Multiple-agent detection schemes in all three technology areas that rely upon differential responses and pattern recognition are currently in the basic research stage and are not expected to reach demonstration before FY 1996.

Odorant detection technology finds application in both explosive detection and drug interdiction. This technology is in the basic research stage and is slated for demonstration in FY 1995.

DNA/RNA probes are useful outside the CBWD area for identifying biofouling organisms and microbes involved in biodegradation. Research in bioremediation, biofouling, signature detection and reduction, and biocorrosion will all involve extensive use of probes coupled with PCR (polymerase chain reaction) technology. The virtual explosion of these techniques is expected to produce new breakthrough technology in each of these areas in FY 1994-1995.

2. Technology Objectives

Technology Objectives — Biotechnology

Technology Set	By 1996	By 2001	By 2006
Materials	• In-vitro synthesis of silk fibers or subunits • Pathways cloned for several thermoplastics and intermediates for composite materials • Cloning of genes for protein-pigment complexes • Chemical synthesis or modification to obtain biodegradable plastics	• Scale-up of solid-state synthesis of fibers • Scale-up of thermoplastic biosynthetic methodology • Characterize optical and electromagnetic properties of pigments • Biodegradable polymers achieved by biosynthesis	• Other high-strength fiber materials developed • Pilot plant developed for composite intermediates • Bonding of protein/pigment complex to fibers and films • Pilot plant developed for microbial or enzymatic synthesis of polymers
Processes	• Scale-up for batch processing of bio-paintstripping; identification of functional enzymes • Identification and isolation of micro-organisms responsible for degradation of TNT in soil • Identification of biodegradative pathways for ammonium perchlorate • Batch recovery of gallium and other strategic materials from low-grade ores • Identification and isolation of enzymes capable of chemical and biological agent degradation	• Complete self-contained bio-paintstripping system for aircraft • Controlled compositing of TNT and other energetic materials contaminating soils • In situ technique or closed bioreactor capable of degrading ammonium perchlorate • Immobilized biochelators for industrial and stream recovery • Bonding or attachment of enzymes to cloth fibers and equipment surfaces	• Additional applications of bio-paintstripping to other DoD equipment and facilities • Scale-up compositing to provide effective bioremediation of ammunition production sites • Pilot plant for degradation or transformation of ammonium perchlorate • Advanced high rate processing systems • Prototype garments and equipment finishes which will catalytically degrade chemical agents on contract
Sensors	• First-generation receptor-based biosensor for chemical agents; hybridoma antibodies for biological agent detection • Identification of fouling organisms • Identification of undersea signature detection	• Robotic chemical/biological detector for specific threats; real-time, receptor-based detector for all threats • Characterization of adhesive; preparation of new polymer coatings • Test of prototype array sensors using pattern recognition	• Robotic, real-time, receptor-based detector system for all chemical and biological agents • Anti-fouling coatings • General classes of sensors for specific targest available

3. Resources

A summary of total S&T funding[19] for this technology is given in the following table.

Funding — Biotechnology ($M)

FY87-91	FY92	FY93	FY94	FY95	FY96	FY97
79	65	66	68	69	71	72

A summary of total S&T funding[19] for this technology is given in the following table.

[19]Funding is derived from programs in the DoD budget. Most programs involve several technologies. It therefore becomes a matter of judgment how many dollars to count toward which technology. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is not to be construed as a precise budgetary quantity.

4. Using the Technology

The DoD biotechnology research effort is diverse and rapidly changing, reflecting rapid progression in the state-of-the-art, and is focused on basic and exploratory development efforts, with very few resources devoted to advanced development and engineering studies. This departure from R&D investment profiles found in conventional technologies is dictated by (1) the recent emergence of non-medical biotechnology as a field of research, and (2) the relatively short lead time and development effort required for commercial realization of basic biotechnological discoveries.

Although the DoD biotechnology program may be said to be in a fledgling stage, it is not apt to fly off in all directions at once. Service programs are closely coordinated and complement one another in content and focus. Advances in one program impacting another are rapidly promulgated. Navy's material program recently produced some advances in production of spider silk at the University of Wyoming. The investigator is now working closely with the Army Natick Research Center, where a strong interest in biological fibers has emerged.

Several DoD-sponsored research efforts have led to spectacular successes. Support of university researchers investigating mussle adhesive has led to commercial development of a biosynthetic mussel adhesive mimic with potential for wide application in both medical and non-medical uses. Research on microtubules formed from membrane lipids conducted at the Naval Research Laboratory has led to a new process for ultra-high solution microlithography. The process has been patented and transferred to industry and is the subject of a continuing cooperative R&D agreement.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

A manufacturing industry has not matured for defense products in the field of biotechnology. Government laboratories and universities are still the primary agents for biotechnology activities. Although it is expected that private industry will establish a manufacturing infrastructure, DoD- sponsored manufacturing has already been started for chemical and biological defense applications (see next section).

2. Projected Industrial Capabilities

A new Process Engineering Facility is under construction at the Army Chemical Research and Development Command at the Aberdeen Proving Ground. It will house a 6,000 ft^2 fermentation facility with the capability of scaling up processes to a maximum of 500 liters. This facility is designed for pilot production of decontamination enzymes and antibodies for use in prototype sensors. It will be available for use by all Services on a space-available basis. In addition to fermenters, the Facility will have labs equipped for cell culture, protein purification, nucleic acid synthesis and sequencing, and extensive analytical capabilities. This facility will substantially increase the DoD capability to begin scale-up of promising processes.

E. RELATED R&D IN THE UNITED STATES

Federal and private sector spending on biotechnology R&D exceeded $50 billion in 1989. The overwhelming bulk of R&D in the U.S. in these areas is financed by the chemical and pharmaceuticals industries. However, their objectives are generally different from the ones described above, although some overlap exists. About $4.3 billion was the result of federal investment. Most R&D within the private sector was performed in the pharmaceutical and agricultural areas. The National Institutes of Health provided 84 percent (or $3.6 billion of the federal spending. DoD was the second largest spender, followed by the National Science Foundation (NSF), DoE, the U.S. Department of Agriculture (USDA), the Environmental Protection Agency (EPA), the Food and Drug Administration (FDA), and the National Institute for Science and Technology (NIST). DoD provided approximately $13 million for university-supported research and an additional $4 million for the University Research Initiative. DoD also provided about $1 million through the small business innovative research (SBIR) program.

NSF supports research in the areas of bioengineering/bioprocessing, biomembranes, bioconversion, biomolecular materials, bioelectronics, and biosensors. Support is provided primarily through ongoing programs in biology, engineering, materials science, and chemistry. In addition, NSF provides funds for three centers with research related to biotechnology materials and processes: the Biotechnology Process Engineering Center, the Center for Development of an Integrated Protein and Nucleic Acid Biotechnology, and the Center for Microbial Ecology.

In the areas of biomaterials and bioprocesses, most industry and university investment has been through government sponsorship, particularly the Offices of Scientific Research of the three Services and the Defense Advanced Research Projects Agency (DARPA). Within the DoD program, this expenditure amounts to about 65 percent of the funds being spent in these areas. Non-government-supported industrial activity has been increasing in the critical chemicals area.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

This section assesses the relative position of various countries with respect to biotechnology, taking into account strengths and weaknesses in basic research and development of products with commercial and military potential. Because of the pervasiveness of biotechnology in health and agriculture, there is virtually universal interest and activity in these fields. Cooperative opportunities exist with most of the NATO countries and many other free world nations as well.

The United States is recognized as the world leader in biotechnology. However, the United States will face considerable competition from Japan, whose strengths include applied biotechnological research, interaction among companies, a diversity of programs, a long-term approach to biotechnology, and strong government support. Biotechnological research and development covers a broad range of areas and includes pharmaceuticals, specialty and bulk chemicals, energy applications, environmental protection, bioelectronics, materials development, and biosensors. Japan is considered a world leader in bioelectronics research and biosensor research and development.

Summary Comparison — Biotechnology

Selected Elements	USSR	NATO Allies	Japan	Others
Biosensor technology	□□	□□□□ ○	□□□□ ○	□ Various countries
Biomaterials: improved bioadhesives, bioplastics, fibers, etc., including recombinant-derived materials	□□	□□□ ○	□□□ ○	□□
Bioelectronics	□□□ ○	□□□ ○	□□□□ ○	□□
Bioprocessing for decontamination or remediation	□□	□□□ ○	□□	□□
Overall[b]	□□	□□□ ○	□□□□ ○	□□ a

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□	broad technical achievement; allies capable of major contributions
□□□	moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
□□	generally lagging; allies may be capable of contributing in selected areas
□	lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators — where significant or important capabilities exist (i.e., 3 or 4 blocks):

+	Foreign capability increasing at a faster rate than the United States
○	Foreign capability increasing at a similar rate to the United States
—	Foreign capability increasing at a slower rate than the United States

Biotechnological research in Japan is carried out by government, industry, and academia. Industrial efforts involve companies with a history of R&D in the biological sciences as well as companies that are primarily involved in other areas but are branching into biotechnology. Many Japanese companies look to U.S. biotechnology companies for collaboration and technology transfer.

European countries such as the UK, Germany, and France are doing well in various areas of biotechnology. Other European countries, although not as strong in biotechnology, are also developing programs. Italy, for example, has adopted a National Research Plan for Biotechnology and a National Program for Bioelectronic Technology Research. Scandinavia, Germany, and The Netherlands lead in innovative approaches to bioremediation.

Biotechnological research and development in Europe covers an extensive range including pharmaceuticals, agriculture, biosensors, bioelectronics, materials development, and environmental protection. Research is carried out by government laboratories, academia, and industry. Industrial efforts have been concentrated in the larger pharmaceutical and chemical companies, although smaller biotechnology companies are also found in Europe, especially in the UK. The larger companies have tended to look to U.S. biotechnology companies for collaboration.

The German government is subsidizes more than 40 research projects. These long-term, high-risk projects would not be possible without some governmental aid. The program was begun in 1985 and, as of 1987, 16 companies in Germany were taking part. More than $10 million was budgeted in 1987 for this program, and government biotechnology spending was $138 million in 1988.

In the Netherlands, the founding of Groningen Biotechnology Center in 1981 combined 10 biotechnologically oriented research groups at Groningen University. Research is conducted in industrial bioorganisms, fine chemicals, industrial enzymes, and environmental biotechnology (treatment of waste).

In the United Kingdom, Cranfield Biotechnology Center at the Cranfield Institute of Technology is especially noted for research on biosensors. The Institute has developed rapid methods for microbial contamination monitors and provides consulting services to industry, including bioaudits to assess contamination in factory work areas.

To help strengthen European efforts in biotechnology, a number of collaborative programs have been established. The European Communities BRIDGE (Biotechnology Research for Innovation, Development, and Growth in Europe) program has recently been planned and would replace the Biotechnology Action Program (BAP) that began in 1985. BAP followed the Biomolecular Engineering Program, which was set up in 1982. Another program supporting biotechnology is the European Research Coordination Agency (EUREKA) program, which involves 19 countries.

The Soviet Union is currently involved in a major biotechnology program. Efforts in biotechnology cover a range of areas including agriculture, pharmaceuticals, bioelectronics, and applications in space. Although the overall Soviet biotechnology capabilities are behind the West, the Soviets are conducting research in some areas that is at least equal to Western efforts.

The Soviet Union has an extensive program in biotechnology research, which is concentrated in a relatively small number of R&D centers located primarily in Moscow, Pushchino, Novosibirsk, and Leningrad. Although only a few Soviet researchers are believed to be performing research at the level of their counterparts in the West and Japan, others are not far behind. Moreover, in at least one important area, biotechnological research in space, the Soviets hold an advantage based on their long-term space station activity.

The USSR has access to a large body of biotechnology information through scientific exchanges, international symposia, and new joint ventures with foreign firms. Western biotechnology organisms and products are readily available to the USSR. The Soviet laboratories at Biogen have Western biotechnology equipment, including centrifuges, chromatography equipment, spectrophotometers, culture media, automatic pipetters, personal computers, and scintillation counters. In the past two years the Soviets have also purchased amino acid analyzers, hollow-fiber cell culture systems, automated fermentation systems, automated DNA sequencers, and "gene machines" from Western companies.

Eastern Europe is emphasizing training in biotechnology at certain universities, targeting interdisciplinary research and development areas, supporting collaborative projects between academic and industrial entities, expanding and updating laboratory facilities, and building new laboratories with modern equipment. In other parts of the world there is considerable interest but, in most cases, limited capabilities. Cuban efforts are noteworthy. China has an extensive effort.

2. Exchange Agreements

There is a high level of exchange activity in the area of biotechnology. The NATO Panel VII, Working Group of Experts (WGE6) on "Biotechnology Applications in NBC Defense," provides a forum for the common development of standardized methods and equipment in biodetection and decontamination as well as a mechanism for exchange of data.

The Technology Cooperation Program (TTCP) provides a number of mechanisms for exchange in a range of applicable activities. Specific topics under TTCP include some nine active programs in the area of nuclear/biological/chemical (NBC) warfare. Topics of direct interest range from the general area of NBC defense to specific topics such as filter performance and toxicological testing of agents affecting filter performance. Also included in this group is detection and monitoring of chemical and biological agents.

The Army has a number of related exchanges, primarily with NATO, but also with other nations, covering CBW defense topics. Here a primary interest is in materials and equipment for protection and techniques for detection and remediation or decontamination of CBW agents. In addition, biotechnology is an underlying technology for a number of other applications covered by international exchange programs. These applications cover such topics as development of fuels and lubricants, ordnance/energetic material disposal, and potential uses as structural adhesives.

The Navy currently has an agreement with the UK Science and Engineering Research Council (similar in structure and purpose to our NSF) to cooperate and exchange information in the area of molecular recognition. A joint meeting between investigators in both programs is planned for FY 1991.

21. FLEXIBLE MANUFACTURING

21. FLEXIBLE MANUFACTURING

A. DESCRIPTION OF TECHNOLOGY

Flexible manufacturing is the process of production with the capability to respond to changing or new situations. The simplicity of the definition stands in sharp contrast to the complexity of the processes that may be needed to assure manufacturing flexibility. The most important factor to assure flexibility in manufacturing is a well defined product or family of products designed for simplicity in production. The second, and equally important factor, is a quality work force trained to respond to change. When these two factors are present, everything else related to manufacturing are implementation tools. Among these tools are those that come under the heading of CAD, CIM, JIT. The choice of these tools and their effective use are tied to the first essential factors. There is, however, one additional element that is essential to every successful enterprise – process management by people skilled in the use of effective management techniques.

As applied to the higher level of production requirements associated with DoD systems, the application of flexible manufacturing becomes far more sophisticated and often draws from a broad technical base for implementation. One may then find flexible manufacturing is defined as the use of software, hardware, and communication technologies to enhance manufacturing productivity. Flexible Manufacturing is the integration of the total production enterprise through the flexible use of shop equipment, sensors, information and systems technology, and data communications coupled with new managerial philosophies that improve organizational and personal efficiency. In the broadest sense, flexible manufacturing includes: integrated product development, manufacturing, integrated data bases, inventory management systems, and paperless logistics support. The flexible manufacturing environment requires significant changes to industrial methods, industrial processes, procedures and organizational structures. These concepts allow the alliance of Defense and private sector industrial capability to provide solutions for supporting flexible and responsive manufacture of both weapon systems and commercial products. The implementation of flexible manufacturing technology offers strong potential to revolutionize the factory environment to meet the challenges of today – the need to improve productivity, time to market, product quality and reliability, as well as to reduce costs.

Typical kinds of flexibility include: the ability of production equipment to quickly shift from one part, assembly or product to another; the ability to smoothly react to major, rapid changes in required production volume; the ability to quickly alter product performance characteristics and rapidly move the changed product through production; the ability to rapidly and effectively incorporate new technologies; and the ability to react quickly to the changing needs and requirements of customers, trading partners and suppliers.

Technology Sets in Flexible Manufacturing

- Product data definition for automated manufacturing
- CAD/CAM/CAE/CAPP
- Databases and database management
- Communications and networking
- Intelligent software interfaces

Integration of factory information systems is crucial to achieving these capabilities. Flexible manufacturing integrates:

- Simulation
- Planning
- Dynamic Scheduling
- Material Management
- Maintenance, Diagnostics, Prognostics
- Process Control
- Training
- Testing and Quality Control

Supporting information systems can "empower" the work force, reduce indirect labor and layers of supervision, facilitate total quality management and just-in-time management, increase the flexible control of work cells, and enable the cost-effective manufacture and assembly of low volumes of discrete parts. Flexible manufacturing is directed at the intra- and inter-enterprise level, rather than toward specific manufacturing equipment or operations. Some of the tools and technologies developed to support advanced flexible manufacturing systems include: simulation tools, computer aided design (CAD), computer-aided engineering (CAE), product data exchange tools, group technology (GT), computer-aided process planning (CAP), factory scheduling tools, databases, and data-driven management information systems (DDMIS).

Flexible production capabilities are of primary importance to the Department of Defense for the following reasons:

1. When the DoD draws from the commercial market, a flexible manufacturing facility provides the capability for continuous introduction of new technology without major additional capital investments. As a consequence, one can anticipate continuous improvement in function and quality without an associated cost detractor.

2. DoD often requires unique components to satisfy military system needs. These requirements are frequently satisfied by a defense industrial sector using dedicated facilities. A flexible production capability could eliminate the need for a dedicated military facility, reduce component costs, increase the potential for early introduction of new technologies and avoid the necessity for continuing to build up inventory in anticipation of sourcing problems.

3. DoD can not afford to maintain a unique defense industrial base in anticipation of future surge requirements. DoD, however, must be assured that a timely response to reasonable surge demands is available. Maintaining a dedicated defense industrial base is unacceptable on two accounts: The cost is prohibitive and the need to continue to produce military systems to sustain continuous production will result in the proliferation of military equipment in markets that may be detrimental to the United States and World Peace. A potential solution is to provide incentives for industry to develop production capacity capable of responding to a new or changing set of requirements in response to sudden military demands and implies flexible manufacturing.

B. PAYOFFS

1. Future Weapon Systems

Every weapon system is dependent on a robust industrial base. The impact of flexible manufacturing is to produce cost–effective, reliable and capable systems on manufacturing facilities which are capable of meeting low volume needs while providing rapid expansion to wartime demands. Flexible manufacturing is an essential capability since it enables:

- Increased worldwide supportability
- Increased weapons systems availability
- Compressed development to deployment time
- Reduced safety spare stocking levels
- Improved quality of manufactured items
- Expanded capability for on–site diagnostics and remote troubleshooting.

Flexible manufacturing has become increasingly critical to both commercial and defense industries. In the commercial marketplace customers demand a rapid flow of new products, while continuing to demand higher quality with maintained or reduced price. To the manufacturer, these demands result in steadily shrinking production volumes, intense pressure for rapid product introduction, and intense pressure to reduce product design, development and manufacturing costs, while maintaining or increasing product quality. In defense production, the need to maintain performance superiority in the face of declining budgets and increasingly uncertain military needs leads to exactly the same results for the manufacturer — demands for shorter development times, reduced costs in all areas, smaller production volumes and increased quality.

Military production runs are commonly limited to small numbers, thereby resulting in very high costs and a significant level of defects. Commercial production practices are moving towards low–volume, flexible manufacturing. While the demands are the same, there are very important differences between the defense manufacturing environment and the commercial environment: very small volume production runs of very valuable products over long timeperiods; requirements for conducting product development and production with very large multi–enterprise nation–wide and even international teams; the need to support the product for time periods close to a half century; design and production requirements set by the customer; constant detailed review of technical and cost performance by the customer; the need to incorporate leading edge technologies in new products; and long times between new product introduction. Nevertheless, defense manufacturing enterprises have enough in common with commercial enterprises to learn from them and to incorporate commercial successes, appropriately tailored, into flexible defense manufacturing. The adoption of this technology by military system manufacturers should make possible dramatic reduction in costs and defects. Further development of new products involves the simultaneous interaction marketing, research, engineering, and manufacturing functions. The shorter development times and lower costs being achieved by this process in the civilian sector are also achievable in the development and manufacturing of military systems.

2. Potential Benefits to the Industrial Base

Flexible manufacturing technologies are often enterprise–level initiatives—not just production subsystems—that require expertise and skills among managers, designers and workers. Each industry and enterpise faces unique challenges and needs. The potential benefits to the industrial base are many:

- Increase cost competitiveness of US Manufacturers
- Shorten product cycle development time
- Reduce product development costs
- Improve utilization of capital equipment
- Improve productivity of manpower resources.

C. S&T PROGRAM

1. Summary Description of Plan for Technology Development

a. Product Data Definition for Automated Life Cycle Support

(1) Objective

Development of standards for the definition and exchange of product data for all DoD systems from development through logistics support.

(2) Development Milestones

- Establish robust standard product definitions for a limited set of part classes and applications, with the first set being machined mechanical parts (FY 1994).
- Establish full testing and validation methodology based on the initial standard definitions (FY 1994).
- Establish transition tools to convert existing data to computer interpretable format (FY 1995).
- Fully-developed file exchange capability based on the initial standard definitions and limited data base capability (FY 1996).
- Address and develop method of integration into CAE architecture.

b. CAD/CAM/CAE/CAPP

(1) Objective

Establishment of an architecture for the integration of design, engineering, process planning, and process information including the capability for exploring alternate approaches and achieving optimized solutions through simulation.

(2) Development Milestones

- Develop tools for component selection, performance simulation, and substitution (FY 1993).
- Incorporate design methods which use object-oriented data and encourage designs for reliability, producibility, and supportability for select products (FY 1994). Develop technologies for improving man-machine interfaces (FY 1995). Develop concepts for better utilization of existing design data for new product models and reduction of production costs (FY 1995).

- Develop an integrated architecture for design and manufacturing process requirements (FY 1995).
- Develop new design tools and algorithms (FY 1995).

c. Data Bases and Data Base Management

(1) Objective

Development and implementation of the technologies, standards, and products necessary to coordinate and synchronize the simultaneous use of multiple, heterogeneous, autonomous data bases in order to provide the correct, complete information in forms usable by both computers and humans.

(2) Development Milestones

- Develop information exchange standards (FY 1995).
- Develop intelligent software interfaces (FY 1995).
- Define data base models to support design, analysis, simulation, production, life cycle support, and enterprise planning and management (FY 1996).
- Demonstrate effectiveness of data base as a management tool (FY 1996).
- Establish migration paths to transition from existing data systems to new data base models (FY 1997).

d. Communications and Networking

(1) Objective

Development of technologies and standards to improve communications and facilitate transmission of large amounts of data at high speeds within and beyond the enterprises engaged in flexible manufacturing.

(2) Development Milestones

- Develop intelligent software interfaces for object-oriented data bases (FY 1994).
- Develop open architecture for networking of enterprise elements and the enterprise with customers and suppliers (FY 1994).
- Test new communications concepts for effectiveness and adaptability (FY 1995).
- Test the multidimensional capability of networking (FY 1996).

e. Enterprise Integration

(1) Objective

Support of activities furthering continuous improvement in all inter- and intraenterprise functions through the creation of technologies and standards by which multivendor interoperable information systems are developed.

(2) **Development Milestones**

- Improve adaptive manipulation of dimensional objects (FY 1994).
- Develop persistent object, i.e., object-oriented data bases (FY 1995).
- Develop real-time cross-coupled control in feedback loops (FY 1995).
- Establish a multi-industry sector framework based on the concepts of objectoriented data bases and real-time, cross-coupled controls (FY 1996).
- Test the integration networking concept to demonstrate feasibility and adaptability (FY 1996).

f. **Intelligent Software Interfaces**

(1) **Objective**

Development of software concepts and capabilities to allow uninhibited information exchange across disparate software interfaces.

(2) **Development Milestones**

- Develop concept of intelligent transfer of information across software interfaces (FY 1995).
- Develop open architecture for controllers (FY 1995).
- Demonstrate ability of unencumbered, uninhibited data flow across software and software-hardware interfaces (FY 1996).
- Demonstrate manipulation of dimensional objects with intelligent software (FY 1996).

2. Technical Objectives

Technology Objectives — Flexible Manufacturing

Technical Area	By 1996	By 2001	BY 2006
Product Data Definitions for Automated Life Cycle Support	• Continue development of product definitions • Test and validate methodology and begin implementation	• Design all new weapons systems in standard product format • Continue development of more productive and automated tools for transitioning from legacy data to new product moels • Implement data definition at parts level and extend to systems level • Integrate into CAE structure	• Standard product data in wide use nationally, for all product designs • Fully implement at all levels of design and manufacture
CAD/CAM/CAE/CAPP	• Identify existing design tools • Develop an integrated design tool (architecture, mechanical, hydraulics, electrical, and software design, manufacturing and support) • Develop new design tools and algorithms • Develop architecture for universal controller • Improve man-machine interfaces (sensory controls)	• Develop voice interactive man-machine interface protocols • Develop the capability to capture and re-use design components • Develop the capability for collaborative design • Develop knowledge base concepts for engineering design and manufacturing • Implement design tools on new weapon system designs • Implement next generation controllers • Implement sensory controls	• Apply integrated design architecture and product data to shop floor control
Database and Database Management	• Define database models to support design, analysis, simulation, production, life cycle support, and enterprise planning, financial and administrative functions • Define generic database of integrated enterprise • Demonstrate effectiveness of database as a management tool	• Demonstrate consensusderived industry standard distributed, object-oriented databases • Demonstrate effectiveness of enterprise integration and value to production of weapon systems • Transition selected weapon systems to full support in new database model	• Establish full integrated weapons database to facilitate design, procurement, manufacturing, training, repair and overhaul, and administrative functions • Integrate concept into subcontract and supplier base

Technology ObjectivesFlexible Manufacturing (Continued)

Technical Area	By 1996	By 2001	BY 2006
Communications and Networking	• Develop concept of fully distributed scalable communication networks serving manufacturing enterprise needs based on intelligent software interfaces • Demonstrate robust integrated manufacturing planning, material procurement and subcontracting, production control, and shop floor routing through linkage to knowledge-based planning tools for timely delivery to assembly stations	• Implement pilot programs of robust integrated networks • Develop network prototocols to transfer data between government and contractors and suppliers	• Implement seamless networking in defense and industrial base
Enterprise Integration	• Develop object-oriented databases, intelligent controllers, and adaptive manipulation of objects	• Continue development of controllers • Apply database concepts and adaptive manipulation	• Promote integration concept across an entire industry sector
Intelligent Software Interfaces	• Improve methods, software, and hardware for improved object recognition in terms of product definition data	• Apply to parts recognition and manipulation, and the assembly of parts	• Implement in the base

3. Resources

Funded programs in this area are to be found in RAMP, CALS, and DARPA. A summary of funding for flexible manufacturing relative to the above functions is given in the following table.

Funding — Flexible Manufacturing ($M)

FY87-91	FY92	FY93	FY94	FY95	FY96	FY97
105	25	28	29	31	32	31

4. Utilizing the Technology

Defense industries and depots have begun to employ elements of flexible manufacturing. Through the decade of the 1980s many companies installed computerized production equipment of various kinds, e.g., composites tape laying equipment, four- and five-axis numerical control machines, robots, and wire harness fabrication machines.

The capability and flexibility of individual computerized design, finance, and manufacturing systems has also steadily increased. Computer-aided design (CAD) systems transitioned from two-dimensional to three-dimensional design. In many companies the CAD systems have been interfaced to a variety of design tools (stiffness, stress, thermal, circuit performance, etc.) to create computer-aided engineering capabilities. Computer-aided process planning (CAPP) systems have become more and more automatic, using data bases of previous plans, incorporating knowledge of shop equipment, and in some cases performing preliminary economic analyses. Systems for assisting in the generation of numerical control instructions for machines have steadily become more capable, with some being fully automatic for limited classes of parts. Simulation of a wide variety of factory operations has increased machine utilization and simplified scheduling. Scheduling systems have become increasingly sophisticated, with some companies employing Material Requirements Planning (MRP), and an increasing number upgrading to Manufacturing Resource Planning (MRPII). The latter integrates material management and shop floor control.

During the last half of the decade, companies started to address the problems associated with the interconnecting myriad of existing capabilities. The difficulty and expense has prohibited large-scale integration. Where the need existed to transfer product data from company to supplier and company to trading partner (as in multi-enterprise teams for B-2 and ATF), the only workable solution has been to mandate the use of one CAD system (usually that of the prime contractor) by all partners.

Aerospace and defense industries have begun to employ flexible manufacturing in an evolutionary manner. The Navy, through the Rapid Acquisitions of Manufactured Parts (RAMP) program, is providing selective support to the use of promising flexible manufacturing applications, including feature-based CAPP, integrated data driven information systems, and demonstrated use of advanced PDES product data for machinery and electrical products. RAMP technology is transitioning to five Navy depots in FY 1992 as well as initiating a demonstration for application in the small business base in the United States.

Several other notable examples are the FCIM facility at Hughes Aircraft (El Segundo), the Avco-Lycoming facility at Stratford, CT, and the Texas Instruments' HARM production line. Rock Island and Watervliet arsenals have undertaken significant efforts of integration as a part of REARM.

D. LEVERAGING INDUSTRIAL BASE CAPABILITIES

1. Current Industrial Capabilities

The non-defense flexible manufacturing industrial base is more extensive than that of defense and is growing. This industrial base can be thought of in two parts: the companies who supply flexible manufacturing hardware and software products to the manufacturing companies, and the manufacturing companies themselves. The commercial manufacturing industrial base is much larger than defense and can be much more selective in its acquisition practices. Thus, it can provide a much stronger influence on the suppliers of flexible manufacturing products than the defense sector. Hence, the strategies and products employed by commercial industry are of great importance to DoD and its contractors, since they will greatly influence the R&D base and the products available to defense producers. The entire industrial base (defense and non-defense) must be utilized for both the technical and managerial resources pertaining to flexible manufacturing.

Several key flexible manufacturing trends are evident in the commercial industrial base. Most large commercial enterprises are focusing their flexible manufacturing efforts on integrated information systems and management initiatives including supplier improvement programs, TQM, IPPD, activity-based accounting, and training and education. A number of major corporations are demanding integrated information systems from their suppliers. The most visible example is General Motors' C4 program. The key ingredient in this thrust for short-time-to-market, lower costs, and higher quality is the development of an internal integration architecture to which all new products must comply. One piece of the architecture involves the CAD-to-CAD problem noted above. To solve it, GM plans to eliminate 83 percent of the different makes of CAD systems currently in use, and partially underwrite the suppliers' cost of integration into their architecture.

Many major corporations now have active supplier improvement programs. These are generally focused on improving the degree of integration between the prime and its suppliers to improve the flexibility inherent in the relationship. The benefits foreseen from such programs include schedule compression, quality improvement, cost reduction, and supplier modernization. Greater flexibility is to be achieved through greater integration of information systems between prime and supplier, particularly in scheduling systems and electronic delivery of product and process data, manufacturing process and equipment upgrading, and partnership rather than adversarial relationships in all matters especially in contracting.

Extensive investments have been made in NC controlled and DNC equipment for use in individual machining operations and the creation of work cells. Investments to integrate the entire factory have lagged considerably. A recent survey of operating CIM systems has brought to light the fact that in most instances the CIM investment was made only as a necessity of last resort. Automation of assembly operations have been much more extensive. However, it must be recognized that most of these investments have been and are being made by the large corporation. The small companies, the bulk of the supplier base, who product 70 to 80 percent of all parts, are limiting their investments to stand-alone machines and work cells. The use of MRP type and other shop-related software is limited even to a greater degree.

2. Projected Industrial Capabilities

Industry has begun to recognize that large-scale, sustained efforts are required to develop the technologies and products necessary to integrate computer-based systems. Industry is also recognizing that management philosophies must be changed to accompany technology advances if the potential of flexible manufacturing is to be achieved. Individual companies and groups of companies have formed coalitions to pursue solutions to achieve critical mass of resources and reduce financial risk.

One such mechanism has become known as strategic partnerships. Several of these have been formed between groups of non-competing companies, such as aerospace, automotive, and software companies, to create products which will solve integration problems of the user partners. More visible at the pre-competitive consortia, such as CAM-I, COS, CFI, PDES Inc., NCMS, and SEMATECH. These consortia support projects to solve common problems of integration. For example, SEMATECH has a CIM Architecture project, NCMS has an Integrated Operations group of programs, and CAM-I has a Computer-Integrated Enterprise project. PDES Inc. was formed solely to accelerate the development of product data exchange standards. Management issues are also addressed by some of the consortia. For example, the CAM-I Advanced Cost Management project is substantially responsible for much of the recent progress in activity-based costing.

E. RELATED R&D IN THE UNITED STATES

1. R&D in Other Agencies

The National Science Foundation (NSF) sponsors basic research in the underlying software technology, with an emphasis on theory. Although moderate-scale prototype engineering activity is occasionally undertaken, most NSF support is provided to individual researchers working on theoretical problems.

NASA is executing a multi-center coordinated effort at four of its field centers called "The NASA Initiative in Software Engineering (NISE)." The focus of NISE is on the producibility of very large and complex software systems with ultra-high reliability requirements. These efforts include: software reuse; tool creation and evaluation; methodology capture and quantification; and standardization for high risk software tools, techniques, and components.

NIST has focused significant R&D attention on flexible manufacturing. Research includes: (1) formal methods for the specification and verification of manufacturing requirements; (2) quality assurance techniques, which apply static analyses to the requirements and design, followed by the testing based on statistical methods; (3) a framework of verification and validation techniques, and (4) PDES. In November 1990, DoC and DoD executed a Memorandum of Understanding to jointly accelerate the development of PDES. NIST's role in the US standards community is particularly important in flexible manufacturing because of the critical importance of national and international standards covering aspects of information integration and communication.

The Advanced Manufacturing Research Facility (AMRF) and the regional centers are also playing an important role in developing elements of flexible manufacturing and transferring that knowledge to industry.

DoE also has significant activities in flexible manufacturing, in both information integration and fabrication. There is an active effort in development of PDES, as well as in integration of its internal information systems. DoE is sponsoring a major effort to develop a flexible system for precision machining which is of considerable potential value to the defense industry.

The DoD Manufacturing Technology Program has supported a number of projects that have dealt with computer-integrated manufacturing and are continuing to do so. One of the earliest projects was ICAM (Integrated Computer-Aided Manufacturing), followed by ECAM (Electronic Computer-Aided Manufacturing). More recent integration projects were REARM, the modernization of Rock Island Arsenal and Watervliet Arsenal, based on the CIM concept. One recent example is the development of the next generation controller (NGC). The Army, Navy, Air Force, DARPA, DSIO, and DLA are active participants.

2. R&D in the Private Sector

The suppliers of information systems are the richest source of R&D in the flexible manufacturing area. Their R&D programs, both long term and shorter term (e.g., product directed), are also very active in standards bodies which are of considerable importance. In response to growing pressure from users, the suppliers are now seriously addressing methods and products to integrate their legacy product lines. A most encouraging development is now serious dialog between major suppliers directed at the issue of ongoing effective integration of legacy products.

In addition to the strategic partnerships and consortia, there is a great deal of individual private sector R&D in flexible manufacturing, although most of it is relatively short term and closely held. Many companies are pursuing modest scale expert systems for a variety of enterprise processes from process planning to marketing. In general, most large companies are addressing product data exchange, integration of purely text systems, and integration of inventory and scheduling systems. Selected ongoing efforts are listed below:

- **New data base technology, especially for the management of objects over a distributed network.**

- Libraries of reliable, reusable program components, now possible due to object-oriented technology.
- Continuing improvement in computer-aided software engineering (CASE) tools.
- Continuing efforts in PDES and IGES.
- Development of the architecture of product life cycle.
- Hardware development in such areas as sensors, vision, robotics, error compensation in machine tools, voice actuation, statistical process control, knowledge base systems, neural networks, networking, and communications, all potential elements of significant importance in flexible manufacturing.

F. INTERNATIONAL ASSESSMENTS

1. Technology and Industrial Base

The following technologies are indicative of the capability of a nation in flexible manufacturing:

- Enterprise Integration Architecture
- Product Data Definitions and Exchange
- Distributed Data Bases and Processing.

The table on the following page provides a summary comparison of the United States and other nations for selected aspects of the technology.

The USSR has demonstrated strong theoretical capabilities in computer science. Soviet researchers have mastered numerous techniques for automation of industrial processes. Institutes and plants supporting military R&D and productions are likely to be the first to assimilate new techniques. Flexible manufacturing technology, however, continues to be an area of serious deficiency, much of it stemming from a shortage of computers, especially microcomputers and supercomputers, machine tools, and from reliability problems, especially with peripherals. Computer-to-computer networking is rare except in high-priority weapon applications. The situation is exacerbated by the poor quality of public telecommunications and poor technical communications among S&T professionals.

Both Japan and Europe are placing considerable emphasis on the development of flexible manufacturing technologies. Japan has led the world in development and utilization of advanced management philosophies, including integrated product and process development, TQM, training, and education. Japanese workers are considered to be the best educated, trained, and motivated in the world, a result of years of sustained emphasis throughout Japan. Through the middle of the 1980s, Japanese industry tended to apply these philosophies to industrial and consumer products which involved relatively long production runs of relatively standard products. Japanese factories have a strong experience base in the use of flexible manufacturing equipment, particularly in world class CNC machine tools and flexible manufacturing systems (FMSs). Indeed, some of their factories can literally operate with the "lights out."

However, from the middle of the decade through the present, Japanese companies have recognized the increasing market trends requiring shorter product lives and faster

Summary Comparison – Flexible Manufacturing

Selected Elements	USSR	NATO Allies	Japan	Others
Enterprise integration architecture	□	□□□□ –	□□□ –	
Product data definitions and exchange	□	□□	□□	
Distributed databases and processing	□	□□□ ○	□□□ ○	
Overall[a]	□	□□	□□	□□

[a] The overall evaluation is a subjective assessment of the average standing of the technology in the nation (or nations) considered.

LEGEND:

Position of other countries relative to the United States:

□□□□	broad technical achievement; allies capable of major contributions
□□□	moderate technical capability with possible leadership in some niches of technology; allies capable of important contributions
□□	generally lagging; allies may be capable of contributing in selected areas
□	lagging in all important aspects; allies unlikely to contribute prior to 2000

Trend indicators – where significant or important capabilities exist (i.e., 3 or 4 blocks):

+	Foreign capability increasing at a faster rate than the United States
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–	Foreign capability increasing at a slower rate than the United States

introduction of new (or modified) products, and have begun to direct their management techniques and production equipment toward more flexibility in manufacturing. In addition, the Japanese have mounted considerable R&D and product development effort in many of the critical technology sets of flexible manufacturing. The Japanese have formed strong partnerships among government, industry, and academia to attack these problems. Their proposed Intelligent Manufacturing Systems (IMS) effort is focused on integration of enterprise systems and the creation of an enterprise integration architecture. Their antisoftware crisis project to develop an effective approach to software engineering is expected to yield a number of products to aid in the implementation of flexible manufacturing. Japanese companies are also developing an operating system for distributed real-time processing for their new generation of 32- and 64-bit microprocessors.

The NATO countries have strong capabilities in flexible manufacturing technologies, and the European Community is supporting massive efforts in this area as well as in closely related ones. Large-scale projects are sponsored by a number of EC-wide programs. Two of them are of particular interest to flexible manufacturing: European Strategic Programme for Research and Development in Information Technology (ESPRIT) and European Research Coordination Agency (EUREKA). Projects normally are conducted by industry/academia teams, 50 percent funded by the EC.

To date, ESPRIT has supported more than 400 projects, many of which directly focus on flexible manufacturing. Two examples are the Portable Common Tool Environment (PCTE) and the European CIM Architecture (AMICE) projects. The PCTE project is emphasizing the development of common software interfaces. The AMICE project (42M ECU-European currency units) is developing an Enterprise Integration Architecture, and has already submitted the basic architecture framework for international standardization.

EUREKA, with a total cost of approximately 6.4 billion ECU, promotes collaboration through coordination. Two of the key EUREKA projects are EUREKA Advanced Software Technology (EAST) and European Software Factory (ESF). Both are focused on aspects of software integration. A key new program is the European Software and System Initiative (ESSI). ESSI is aimed at increasing software productivity, and is funded at 500 M ECU from 1990 to 1994. Additional emphasis on the use of formal methods to develop highly reliable software has led to a European lead in many areas. All of these software developments support flexible manufacturing technology.

2. Exchange Agreements

In defense activities there is little cooperation pertaining to flexible manufacturing technology. Cooperative programs are ongoing in related software and software tools. The NATO Defence Research Group (DRG) programs in operations research and longterm research for air defense provide a mechanism for exchange of information on requirements for improved software technology. The Technology Cooperation Program (TTCP) sponsors a group on software engineering as well as a range of other applicable exchange activities, including computing technology, trusted computer systems, and machine and system architecture. The OSD CALS Office has executed a Data Exchange Agreement with the French MOD on the subject of CALS, with a particular interest in product data exchange. The Services also have exchange activities, primarily with NATO nations. Ongoing Service exchange programs in software development methodologies, techniques, and tools contribute directly to the US understanding of foreign software engineering technologies. One area in particular needs to be recognized and given greater attention to the development of standards. Lack of coordination of US standards with ISO standards can significantly affect future US market share and the opportunity to generate funds for supporting research and development in flexible manufacturing.